Understanding growth and physiological responses to slash management, thinning and fertiliser application in short-rotation tropical acacia plantations

by

Vu Dinh Huong

M.Sc. in Silviculture (Nong Lam University, Vietnam)

Submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

University of Tasmania, June 2016

Declaration of Originality

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief, contain no copy of material previously published or written by another person, except where due reference is made in the text of the thesis. This thesis does not contain any material that infringes copyright.

(signed):............................. ....2 June 2016

Authority of access

This thesis may be made available for loan. Copying of any part of this thesis is prohibited for two years from the date this statement was signed; after that time limited copying and communication is permitted in accordance with the Copyright Act 1968.

Statement on published work

The publishers of the paper comprising Chapter 3 hold the copyright for that content, and access to the material should be sought from the respective journals. The remaining non published content of the thesis may be made available for loan and limited copying and communication in accordance with the Copyright Act 1968.

June 2016

Declaration of co-authorship

The following people and institutions contributed to the publication of work undertaken as part of this thesis:

Vu Dinh Huong, School of Land and Food, University of Tasmania, Australia; CSIRO Land and Water, Hobart, Tasmania 7001, Australia; and The Vietnamese Academy of Forest Sciences (Candidate).

Dugald Close, School of Land and Food, University of Tasmania, Australia (Supervisor).

Daniel Mendham, CSIRO Land and Water, Hobart, Tasmania 7001, Australia (Co-supervisor).

Sadanandan Nambiar, CSIRO Land and Water, Canberra, ACT 2601, Australia.

Le Thanh Quang, Vietnamese Academy of Forest Sciences, Vietnam.

Pham The Dung, Vietnamese Academy of Forest Sciences, Vietnam.

Author details and their roles:

Manuscript 1: Improving productivity and sustainability of successive rotations of *Acacia auriculiformis* plantations in South Vietnam

Located in Chapter 3

Vu Dinh Huong (70%) designed and conducted the experiment, analysed the data and wrote the manuscript. Sadanandan Nambiar, Le Thanh Quang, Daniel Mendham and Pham The Dung (30%) contributed to experimental design and edited the manuscript.

Manuscript 2: Growth and physiological response of *Acacia auriculiformis* plantations to mid-rotation thinning, application of phosphorus fertiliser and organic matter retention in South Vietnam

Located in Chapter 4

Vu Dinh Huong (70%) designed and conducted the experiment, analysed the data and wrote the manuscript. Dugald Close and Daniel Mendham (30%) contributed to experimental design and edited the manuscript.

Manuscript 3: Growth and physiological responses to intensity and timing of thinning in short rotation tropical *Acacia* hybrid plantations in South Vietnam

Located in Chapter 5

Vu Dinh Huong (70%) designed and conducted the experiment, analysed the data and wrote the manuscript. Dugald Close and Daniel Mendham (30%) contributed to experimental design and edited the manuscript.

We the undersigned agree with the above stated "proportion of work undertaken" for each of the above published or submitted peer-reviewed manuscripts contributing to this thesis:

- Vu Dinh Huong, School of Land and Food, University of Tasmania, Australia; CSIRO Land and Water, Hobart, Tasmania 7001, Australia; and Vietnamese Academy of Forest Sciences (Candidate).

Signature: June 2016

- Associate Professor Dr. Dugald Close, School of Land and Food, University of Tasmania, Australia (Supervisor).

Signature: June 2016

- Dr. Daniel Mendham, CSIRO Land and Water, Hobart, Tasmania 7001, Australia (Co-supervisor).

Signature: June 2016

- Dr. Sadanandan Nambiar, CSIRO Land and Water, Canberra, ACT 2601, Australia

Signature: June 2016

- Mr. Le Thanh Quang, Vietnamese Academy of Forest Sciences, Vietnam.

Signature: June 2016

- Associate Professor Dr. Pham The Dung, Vietnamese Academy of Forest Sciences, Vietnam.

Signature: June 2016

Publications

Refereed journal article

Chapter 3:

Huong VD, Nambiar EKS, Quang LT, Mendham D, Dung PT (2015) Improving productivity and sustainability of successive rotations of *Acacia auriculiformis* plantations in South Vietnam, Southern Forests: a Journal of Forest Science, 77:1, 51-58, DOI:10.2989/20702620.2014.983360.

Manuscripts for refereed journals in internal CSIRO Review

Chapter 4:

Huong VD, Mendham DS, Close DC (2016) Growth and physiological response of *Acacia auriculiformis* plantations to mid-rotation thinning, application of phosphorus fertiliser and organic matter retention in South Vietnam. Target is to submit to Forest Ecology and Management: (under internal CSIRO review).

Chapter 5:

Huong VD, Mendham DS, Close DC (2016) Growth and physiological responses to intensity and timing of thinning in short rotation tropical *Acacia* hybrid plantations in South Vietnam. Approved for submission after internal CSIRO review. Submitted to Tree Physiology (Manuscript number: TP-2016-204).

Conference publications

Chapter 3:

Huong VD, Nambiar EKS, Quang LT, Mendham D, Dung PT (2014) Improving productivity and sustainability of successive rotations of *Acacia auriculiformis* plantations in Vietnam. In: IUFRO Acacia 2014 Conference 'Sustaining the Future of Acacia Plantation Forestry' 18 – 21 March 2014, Hue, Vietnam, Compendium of Abstract. p. 36.

Abstract

In Vietnam acacia plantations are an important resource for the production of pulpwood and sawn timber. However, research is needed to support sustainable and profitable production over successive rotations. This thesis reports on results from three field experiments which were conducted on *Acacia auriculiformis* and *Acacia* hybrid species in Vietnam. The experiments explored the growth and physiological responses of acacia to slash management, thinning and fertiliser application to test the hypothesis that constraints in nutrients and/or water and light resources were constraining the growth of acacias, both at establishment, and later in the rotation. The rationale for focusing on resource constraints is that they offer some opportunity for management intervention.

The first study explored the impacts of contrasting slash and litter management techniques applied at the start of the second rotation and re-applied at the start of the third rotation with an additional phosphorus fertiliser treatment during the inter-rotation phase of *A. auriculiformis* plantations. Removal of slash and litter after harvesting the first rotation removed 20.2 Mg ha^{-1} biomass, containing 169.6, 13.9, 76.3, and 25.1 kg ha^{-1} of N, P, K, and Ca, respectively, from the site. Greater amounts were removed after the second rotation commensurate with higher productivity and amounts of biomass produced. Growth of trees in the second rotation was significantly higher where slash and litter were retained compared to where they were removed. Soil organic carbon and nitrogen contents were greater (26% and 40% respectively) in treatments with slash and litter retained compared to initial levels before the treatments were applied. In the second rotation, there was no growth

response to P fertiliser but extractable soil P declined during this period. In the third rotation there was a positive response to added P fertiliser. Slash and litter retention along with improvements in the genetics of planting stock, weed control and stocking with each rotation resulted in average growth rates increasing from 10.6 m^3 ha^{-1} yr^{-1} in the first rotation (age 7 yr) to 28.3 m^3 ha^{-1} yr^{-1} in the second rotation (age 6 yr) and to 33.9 m^3 ha^{-1} yr^{-1} at age 5 yr in the third rotation. Thus, the results indicated that there is an opportunity to increase and sustain production of *A. auriculiformis* over at least three rotations by integrated management practices promoting better stocking, planting of genetically improved stock, organic matter and nutrient conservation, P fertiliser addition and judicious weed management.

The second experiment investigated how thinning, P fertiliser application and slash retention at age 4 yr interact to affect the physiology and growth of *A. auriculiformis* trees to age 7 yr. The photosynthetic rate (A_{max}) in the thinned treatment was significantly higher than in the unthinned treatment one year after thinning. A combined treatment of thinning and phosphorus fertiliser (P) application increased A_{max}, but A_{max} in the unthinned treatment did not significantly increase when P was supplied. Foliar nitrogen and phosphorus concentrations were greater in thinned than in unthinned treatments. Tree diameter was significantly greater under thinning, but it was not influenced by the application of fertiliser (50 kg P ha^{-1}) and slash and litter retention. The recovery of larger diameter, sawlog sized, timber in thinned treatments was significantly higher than in unthinned treatments. At seven years, the total stand value of wood products in the thinned treatments (including the thinning harvested in year 4) was higher than (5 %) for the unthinned treatments. This experiment supports the practice of mid-rotation thinning of *A. auriculiformis* in these environments to increase the value of these plantations to acacia growers.

Growth and physiological responses of the *Acacia* hybrid plantation to thinning treatments of different intensity at age two and three years were also examined in a field experiment. Three years, after intensive thinning at age two, stand volume was reduced by 15.8 % but average stem diameter was increased by 16.7 %. The moderate thinning regime resulted in no significant loss in stand volume and an increase in average diameter of 7.5 %. After thinning the LAI of the intensively thinned stand recovered rapidly and there was no significant difference between unthinned and thinned treatments one year after thinning. This was associated with decreased litterfall production. Intensive thinning increased photosynthetic rates of the lower crown by 30.4 % in association with increased phosphorus concentration in leaves of 37.5 %. Tree growth was significantly influenced by season and thinning reduced leaf water stress during the dry season. Thinning of *Acacia* hybrid at age 2 or 3 yr resulted in higher leaf-level photosynthesis, enhanced water relations, and improved foliar phosphorus relative to unthinned trees. This suggests that intensive thinning at age two years or moderate thinning at age three years are practices that are likely to confer greater benefit to acacia growers. The investment decision should also account for the market value of different log sizes, the costs associated with harvest of these logs, and the risks associated with managing plantations for sawlog production, including longer rotations.

In conclusion, the productivity of commercial acacia plantations can be maintained and improved by adopting integrated management practices, especially by retaining slash and litter after harvesting to promote soil conservation during the inter-rotation phase. Applying thinning for short-rotation tropical acacia plantations can reduce intraspecific competition in stands for water and light resources and increase the benefits for acacia growers.

Acknowledgements

Financial support for this project was provided by the Australian Centre for International Agricultural Research (ACIAR). The School of Land and Food, University of Tasmania (UTAS), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Vietnamese Academy of Forest Sciences (VAFS) and the Center for International Forest Research (CIFOR) provided the necessary infrastructure and some additional funding for this project.

I would like to thank my supervisors, Associate Professor Dr. Dugald Close (UTAS) and Dr. Daniel Mendham (CSIRO), who initiated this project and have provided me with expert guidance, encouragement and assistance throughout the project. I would also like to thank Dr. Chris Beadle (CSIRO) and Associate Professor Dr. Pham The Dung (VAFS) for their guidance and permission to use a Satellite of the Project ACIAR FST 2006/87 for a field experiment; and Dr Sadanandan Nambiar and Dr. Chris Harwood (CSIRO) for their support and guidance. I thank Dr. Philip Smethurst, Dr. Paul Drake, Dr. Libby Pinkard and Dr. Anthony O'Grady (CSIRO) for their internal review of Chapter 4 and Chapter 5, and Dr. Kerry Bridle (UTAS) for proof reading.

I am grateful to many people have helped make this project a success:

- *Dr. Takeshi Toma (Forestry and Forest Products Research Institute, Japan) for arranging financial support during the early phase of the study;*
- *Dr. Tony Bartlett, Mrs. Sharon Harvey, Mr. Geoff Morris, Mrs Nguyen Thi Thanh An and Mrs. Nguyen Thi Lan Phuong (ACIAR) for their support during the course of this project;*
- *Mr. Nguyen Xuan Hai, Mr. Nguyen Van Hung, Mr. Pham Van Bon, Mr. Le Thanh Quang and Mrs. Bui Thi Minh Ty (VAFS), Mr. Keith Churchill (CSIRO) and Dr. Alieta Eyles (UTAS) for their assistance in the fieldwork and laboratory work;*

- *Professor Dr. David Ratkowsky (UTAS) for expert statistical advice;*
- *Dr. Tran Lam Dong and Mr. Trieu Thai Hung (VAFS) for useful advice in experiments.*

I also wish to thank my wife (Loan), my sons (Minh and Khoi), my extended-family members and friends for encouragement and moral support that greatly contributed to the achievement of this project.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

%	Percentage
µmol	Micromole
^0C	Temperature (degree Celsius)
A.	Acacia
A/Q	Photosynthetic light response curves
A_{1500}	Light saturated net photosynthesis
ACIAR	Australian Centre for International Agricultural Research
AGROINFOR	Information Center for Agriculture and Rural Development
A_{max}	Maximum photosynthetic rate
ANOVA	Analysis of Variation
APAR	Absorbed photosynthetically active radiation
ATP	Adenosine triphosphate
C	Carbon
CO_2	Carbon dioxide
Ca	Calcium
ca.	Circa
CAI	Current annual increment
CEC	Cation exchange capacity
CIFOR	Center for International Forestry Research
cm	Centimetre
cm^2	Square centimeter
cm^3	Cubic centimeter
cmol	Centimole
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DBH	Diameter at breast height
F	Form factor

FSIV	Forest Science Institute of Vietnam
g	Gram
g_s	Stomatal conductance
H	Height
ha	Hectare
K	Potassium
kg	Kilogram
LAI	Leaf area index
ln	Logarithm
LSD	Least significant difference
LSL	Large saw-log
LUE	Light-use efficiency
M	Million
m	Metre
m^2	Square metre
m^3	Cubic metre
MAI	Mean annual increment
MARD	Ministry of Agriculture and Rural Development
Mg	Million gram
mm	Millimetre
N	Nitrogen
n	Number of observation
NADPH	Nicotinamide adenine dinucleotide phosphate
O_2	Oxygen
P	Phosphorus
PAI	Plant area index
PAR	Photosynthetically active radiation
pH	Potential of hydrogen
p-value	Probability
PW	Pulpwood

R	Rotation
R^2	Coefficient of determination
R_{dark}	Dark respiration
s	Second
SD	Standard deviation
SE	Standard error
SOC	Soil organic carbon
SOM	Soil organic matter
SSL	Small saw-log
t	ton
V	Volume
VAFS	Vietnamese Academy of Forest Sciences
WUE	Water-use efficiency
yr	Year
$\delta^{13}C$	Carbon isotope composition
$\delta^{15}N$	Nitrogen isotope composition
φ	apparent quantum yield
Ψ_{leaf}	Leaf water potential

Chapter 1. Introduction

1.1. Background

Acacia species are widely planted in South-east Asia for many purposes such as the production of paper pulp, firewood, tannin, animal forage and human food (Turnbull et al. 1997). Pure-species plantations of *A. mangium* and *A. auriculiformis* have developed as important plantations species in Vietnam, following seed introductions from natural provenances in Papua New Guinea and north Queensland in the second half of the twentieth century (Nghia and Kha 1998). In early 1960s, almost 20 *Acacia* species have been introduced into Vietnam for trial plantings, especially in South Vietnam. In the 1980s some *Acacia* species such as *Acacia mangium*, *A. auriculiformis,* and *A. crassicarpa* have been introduced for trials (Nghia and Kha 1998). Natural hybrids between *A. mangium* and *A. auriculiformis* were first reported in the 1970s in Sabah, Malaysia (Nghia 2003b). Commencing in 1992, *Acacia* hybrid (combination *A. mangium* Widle. x *A. auriculiformis* A. Cunn. ex Benth) clones were developed from occasional hybrid individuals identified in young *A. mangium* plantatations in Vietnam. Nineteen hybrid clones have been selected for a clonal test established in 1993 at Ba Vi – Vietnam with *A. mangium* Pogaki and *A. auriculiformis* Coen as controls. The results showed that hybrid clones grow faster than parental species with ideal wood quality (Nghia 2003b). Currently in Vietnam, improved planting material of *Acacia mangium* and *Acacia auriculiformis,* and clones of the hybrid between *A. mangium* and *A. auriculiformis* (*Acacia* hybrid) are selected for forest plantations to provide timber for industries including pulpwood, sawlog product, veneers and fibre boards, with small-diameter branches often used for firewood (Harwood and Nambiar 2014). The current acacia plantation area is about 1.1 M ha consisting of 0.6 M ha of *A. mangium*, 0.1 M ha of *A. auriculiformis* and 0.4 M ha of *Acacia* hybrid (Nambiar and Harwood 2014). About half of the total area of *Acacia* plantations in Vietnam is managed by household growers who own less than 5 ha of plantations (MARD 2014). These resources, managed in rotations of 5 to 8 year, are important contributors to the local rural economy and nationally, through supporting wood chip export (~70 %) and furniture industries (~30 %) (Nambiar et al. 2015).

The growth rates of acacia plantations in Vietnam are highly variable, ranging between 10 and 25 $m^3 ha^{-1} yr^{-1}$, depending on site (Forest Science Institute of Vietnam 2010). Harvesting of first-rotation acacia plantations began in the 1990s and the areas under successive rotations are increasing (Phat 2011). Access to new land for forestry is limited, especially in the south, and the growing opportunities for a wood-based economy can only be realized by increasing and sustaining production from the current land base.

For the sustained productivity of short-rotation forest crops in tropical environments, the inter-rotation management (including practices such as harvesting, site management and establishment of the next rotation) is a critical phase, that carries risks as well as opportunities (Nambiar and Harwood 2014). Soil organic matter is a critical factor related to productivity of plantations because it has important roles in sustaining nutrient supply, increasing cation exchange capacity and improving soil structure.

Understanding the nutrient content of litter and tree components can enable the evaluation of nutrient removed off site by different harvesting practices. Harvesting intensity and subsequent management of organic matter and nutrients at sites can have significant impacts on soil and productivity (Nambiar and Kallio 2008, Laclau et al. 2010, Gonçalves et al. 2013, Nambiar and Harwood 2014). Many studies have shown that losses of soil organic carbon and nutrients during the inter-rotation phase can be caused by off-site debarking, whole tree harvesting and burning or removal of slash (Nambiar and Kallio 2008, Laclau et al. 2010, Gonçalves et al. 2013, Nambiar and Harwood 2014, Tistshall et al. 2013). Furthermore, the prevailing practices of many growers involve heavy site disturbances and depletion of site organic matter; practices that are damaging soils and landscapes to the detriment of long-term productivity. A loss in productivity of 21% from the first to the second rotation was observed in a *A. mangium* plantation in South Sumatra using the practice of whole tree harvesting treatment compared to the practice of slash and litter retention (Hardiyanto and Nambiar 2014). Even greater productivity differences have been reported for different harvesting practices in *Eucalyptus grandis* plantations in Brazil (Gonçalves et al. 2008) and *Eucalyptus* hybrid plantations in the Congo (Laclau et al. 2010).

Management practices for ensuring sustainable inter-rotation productivity include deployment of good genetic material, conservation of site resources (eg. slash retention), ensuring tree survival by good planting practice (tree planting technique includes care in placement of roots to ensure good soil-root contact post planting), weed control by manual labour or with herbicides instead of slash burning and repeated ploughing, and nutrient management (adding fertilizer and conserving organic matter: e.g. slash retained at site after harvesting) (Nambiar and Harwood 2014). However, such science-based integrated management is yet to be widely adopted in Vietnam.

Vietnam's timber processing industries are very important for the State's economy. The value of exported wood and wood products was about 6.73 billion USD in 2015, but approximately 65% of the raw materials were imported timbers from several other countries such as Laos, Cambodia, China, United States of America, Malaysia, Thailand, Chile, New Zealand, Germany and Brazil (AGROINFOR 2014). Most *Acacia* plantations in Vietnam have been established and managed over short-rotations for pulpwood production, so they do not yield a high proportion of saw-logs. There are significant economic advantages of sawlog over pulpwood production based on financial analyses conducted for typical small-holders throughout the country (e.g. NPV, US$ 1600 and US$ 1400, were found in plantations for sawlogs and pulpwood, respectively) (Blyth and Hoang 2013). Therefore, Vietnam is considering ways to increase the amount of sawlogs produced from its plantation resource (MARD 2014).

Stem diameter size is a key determinant of log value and can significantly affect harvesting costs, particularly in short-rotation systems. Furthermore, success in the management of plantations of fast growing tropical tree species for the production of large-diameter logs can be achieved by performing intensive and timely silvicultural intervention. There is a trade-off in minimising stem number and thus maximising stem diameter, without sacrificing overall standing volume (Beadle et al. 2013). In acacia plantations, planting densities of $\geq$ 1000 trees ha^{-1} are required to ensure good apical dominance and tree form, and to minimise branching (Beadle et al. 2013). Management for larger diameter logs may require thinning of stem numbers at a suitable time in the rotation to reduce stocking density to a level that allows for high diameter growth on the remaining stems.

Thinning is a silvicultural operation applied to plantations in order to manage quantity and quality of potential saw-logs within forest stands to meet management objectives (Evans and Turnbull 2004, West 2014). Thinning provides intermediate yields and permits salvage of volume that would otherwise be lost when trees die or growth rates slow from overcrowding. The reduction in density brought about by thinning provides more resources for the remaining trees, thereby enabling increased diameter growth. Thinning also provides the opportunity to remove poorer quality stems, thus maximising the benefit of growth responses from reduced stand density (Cassidy et al. 2012, Glencross et al. 2012).

Studies of a range of tropical and temperate tree species have shown that plantations respond differently to thinning depending on the age of the tree at thinning and on the intensity of thinning (Galloway et al. 2001, David 2002, Jaakkola et al. 2006, Comfort et al. 2010). Tree growth is related to site conditions and bio-physical factors that can be explained as a function of resource provision and efficiency of use (Richards et al. 2010). Faster-growing trees are known to have a greater capacity to respond to thinning than slower-growing trees (Evans and Turnbull 2004). The physiological basis for this differential response needs to be elucidated further. There is little research conducted on the impact of thinning and fertilising on acacia plantations in order to maximise tree size and improve wood quality and quantity to meet requirements for acacia growers, wood processors and consumers.

To address issues as outlined a review of the published literature is presented in Chapter 2. The review identifies knowledge gaps regarding the effects of slash retention, thinning regimes and fertiliser application on the sustainable productivity and stand quality of short-rotation tropical acacia plantations. The following research questions were identified that are addressed by this thesis:

(1) Can harvest residue management affect the dynamics of soil carbon and nutrient pools leading to improvement in plantation productivity?

(2) What is the optimal time for capturing a thinning response?

(3) What light, soil water and nutrient resources limit growth response to thinning; and when does the limitation occur?

Therefore, the aim of this study was to explore the growth and physiological responses of acacia species to slash management, thinning and fertiliser application, with a particular emphasis on testing the hypothesis that constraints in nutrients and/or water and light resources are the basis for the response. The rationale for focusing on resource constraints is that they offer some opportunity for management intervention.

1.2. Objectives

The objectives of this study were:

(1) To examine the productivity of three successive rotations of *A. auriculiformis* plantations grown on the same site; describe the dynamics of soil organic matter and

nutrients in relation to harvest residue and nutrient management; and examine the changes in soil properties during the rotation.

(2) To investigate and understand the growth and physiological responses of thinned *A. auriculiformis* stands to the addition of phosphorus (P) fertiliser and slash retention after thinning.

(3) To investigate and understand the physiological constraints that determine differential growth responses in thinned *Acacia* hybrid stands at different stages of development.

1.3. Outline of the thesis

This thesis consists of six chapters, an introduction, a literature review, three experimental chapters and a chapter that summarises the key findings of the thesis and their implications for management. The three experimental chapters are written as journal articles as they have been, or are intended to be, submitted for publication. In brief:

Chapter 1: Introduction

This chapter outlines the background to the development of the thesis, provides research questions, objectives of the study and the thesis structure.

Chapter 2: Literature review

Chapter 2 provides a comprehensive literature review focusing on the dynamics of carbon, water and nutrients in acacia plantations, with a specific interest in plantation productivity over successive rotations. This chapter also reviews tree response to thinning and fertiliser application in order to improve management of *Acacia* plantations for improved productivity and yield of saw-logs.

Chapter 3: Improving productivity and sustainability of successive rotations of Acacia auriculiformis plantations in South Vietnam

Chapter 3 investigates the impacts of slash management on soil properties and growth of *A. auriculiformis* plantations during the inter-rotation phase. This chapter has been published in 'Southern Forests: a Journal of Forest Science'.

To cite this article: Huong VD, Nambiar EKS, Quang LT, Mendham D, Dung PT (2015) Improving productivity and sustainability of successive rotations of *Acacia auriculiformis* plantations in South Vietnam, Southern Forests: a Journal of Forest Science, 77:1, 51-58, DOI:10.2989/20702620.2014.983360.

Chapter 4*: Growth and physiological response of Acacia auriculiformis plantations to mid-rotation thinning, application of phosphorus fertiliser and organic matter retention in South Vietnam*

Chapter 4 examines the hypothesis that the combination of phosphorus fertiliser, slash retention and mid-rotation thinning will optimise resource capture, use and growth of *A. auriculiformis* plantations, and allow for greater sawlog production.

Chapter 5: Growth and physiological responses to intensity and timing of thinning in short rotation tropical Acacia hybrid plantations in South Vietnam

Chapter 5 tests the hypothesis that increasing the level of thinning (decreasing tree density through thinning) reduces the exposure of individual trees to water stress, which extends the daily growth phase and lengthens the growing season on water-limited sites, enhances the photosynthetic capacity, water use efficiency and light-use efficiency of the stand. A comparison of early-age and later-age thinning was undertaken to test the impact of timing of thinning (early and late thinning) on tree responses and resulting volume recovery.

Chapter 6: Summary and implications for management

Chapter 6 presents a holistic and integrated summary of the findings of this thesis and their relation to initial hypotheses and objectives. Implications for management are described, while identifying areas requiring future research.

Appendix: This section contains the published paper.

Chapter 2. Literature review

This literature review is focused on the dynamics of carbon, water and nutrients in plantation forests, to explore the following:

- plantation productivity over successive rotations, and
- tree response to thinning, slash retention and fertiliser application.

It is important to understand these processes in order to improve management of acacia plantations to sustain or/and increase the productivity and yield of saw-logs.

2.1. Soil organic carbon and dynamics of water and nutrients in plantations

2.1.1. Soil organic carbon

Soil organic carbon (SOC) accounts for approximately 58% of soil organic matter (SOM) has a fundamental role in many key edaphic processes, from soil aggregation to plant nutrient supply (Attiwill and Leeper 1987). The quantity of SOM in the soil is dependent on rates of organic matter deposition and decomposition (Vitousek 1984). Soil organic matter improves soil fertility and soil texture (Zinn et al. 2002) by holding soil particles and enhancing water holding capacity, water infiltration, gaseous exchange, soil aggregation and root growth, which allow for ease of cultivation (Scholes et al. 1994). SOM also contributes to enhanced cation exchange capacity (CEC) and retention of base ions (Craswell and Lefroy 2001).

The rate of decrease and recovery of SOC content may vary among tree species. Paul et al.

(2002) undertook a review of 43 studies focusing on the effects of afforestation on soil carbon content. They concluded that C levels in the surface soil usually decreased during the first five years after tree planting, after which time they recovered to the original pre-afforestation level or they increased slightly over this level. The accumulation of SOC in *A. mangium* and *A. auriculiformis* plantations tends to be much higher than under other plantation species like eucalypts (Dias et al. 1994, Garay et al. 2004, Schiavo et al. 2009, Yang et al. 2009, Wang et al. 2010).

Nitrogen-fixing tree species have been reported to have larger effects on SOC in forest soils than other species (Binkley 2005). For example, a review of 19 case studies, showed that increases in soil N were associated with a commensurate increase in C, typically with a ratio of 1 g N resulting in 12 to 14 g increase in soil C (Binkley 2005).

A. mangium and *A. auriculiformis* plantations tend to have high organic carbon levels, although they are planted in soils with a wide range in organic carbon (Sam 2001) . This variation in SOC is associated with soil type and climate (Krull et al. 2004). In sandy and clay soils, steady state values of SOC are typically around 1 - 1.5% and 3.5 - 4.4%, respectively (Körschens et al. 1998). Soil structure and tree crop yields tend not to be related to soil organic carbon at levels over approximately 2% (Greenland et al. 1975, Howard and Howard 1990). However, soils with less than 1% SOC are associated with low yields (Kay and Angers 1999).

Site management using slash retention after harvesting may be important for maintaining SOC in short-rotation plantations (Smethurst and Nambiar 1990, Nambiar et al. 1998, Nambiar et al. 2000, Mendham et al. 2003). Xu et al (2000) indicated that the retention of harvest residue reduced the decline of SOC in an eucalypt plantation two years after planting (cited in Nambiar et al. 2000). However, Mendham et al. (2003) found that more than 50 t ha^{-1} C was contained in double residue treatment at a red earth site (Rhodic Ferrosol soil) had no significant impact on soil carbon pools during seven years of an *E. globulus* plantation.

Short rotation tropical acacia plantations are typically grown in monocultures, based on 5-8 year rotations. Currently clear-fall cutting is the dominant management practice used for short rotation acacia forestry. These high turnover systems can potentially cause losses of SOM, soil organisms and soil function if not managed appropriately (Macedo et al. 2008). Following afforestation, SOM levels in the surface soil typically decrease during the first few years and then recover to the pre-afforestation levels or may became slightly higher (Paul et al. 2002, Norisada et al. 2005). Disturbance caused by land preparation for new planting and a lack of inputs while the trees are in the pre-canopy closure phase is the major reason for this decline (Paul et al. 2002, Gonçalves et al. 2007), in part because the exposed SOM is vulnerable to erosion by rain. In addition, the harvest operations at the end of the second rotation remove a considerable amount of biomass from plantation sites resulting in a depletion of nutrients. For example, when only merchantable wood was removed, the nutrients lost were 47.3 kg ha^{-1} available P, 115.3 kg ha^{-1} K and 15.7 kg ha^{-1} Ca in *A. auriculiformis* plantations in Southern Vietnam (Huong et al. 2015), and 7.8 - 12.2 kg ha^{-1} available P, 73 - 91 kg ha^{-1} K, 267 - 357 kg ha^{-1} Ca and 264 - 371 kg ha^{-1} N in *A. mangium* plantations in South Sumatra, Indonesia (Hardiyanto and Wicaksono 2008).

Losses of SOM following timber harvesting resulted in site deterioration by lowering the cation exchange capacity, reducing soil moisture and increasing soil compaction (Flinn et al. 1980). Loss of SOM and nutrients can be exacerbated by burning of the slash and litter materials after harvesting. This practice, which is used to reduce land preparation costs, is still prevalent in Vietnam (Nambiar and Harwood 2014). Several studies suggests that slash retention after harvesting is vital to maintain SOC and nutrient pools in plantation forests (Gonçalves et al. 2007, Nambiar and Kallio 2008, Titshall et al. 2013, Nambiar and Harwood 2014).

2.1.2. Water

Water is necessary for various important processes in plants such as photosynthesis, respiration, mineral nutrition, enzymatic operations and nitrogen metabolism (Kozlowski and Pallardy 1997a, Landsberg and Gower 1997). Water deficits tend to reduce tree growth directly through effects on cell turgor that in turn influences cell enlargement and differentiation. Indirect impacts include perturbation of various essential physiological processes. Photosynthetic rates tend to decrease with greater water deficit, which is often regulated by the plant through stomatal closure. This process also increases resistance to the diffusion of carbon dioxide (CO_2) to the chloroplasts and results in decreased enzyme activity (Kozlowski and Pallardy 1997b).

Water in the soil-plant-atmosphere system is one of the most important factors affecting tree growth (Waring and Running 2007). Soil water availability is vital for plants that maintain physiologically active foliage during prolonged periods of drought. The amount of water in soil depends on the balance between water input (typically by rainfall) and losses through run-off, drainage, evaporation of intercepted rainfall, soil evaporation and transpiration by plants (Landsberg and Sands 2010a). Key factors affecting soil water holding capacity (that is the stationary storage capacity which is associated with complicated capillarity in the soil layer) include soil texture and structure, soil capillarity, porosity and soil organic matter. Soil capillarity and porosity are also influenced by the density of dead roots, the activity of soil macro-fauna, and the formation of organic mineral substances (Bin et al. 2007).

Bin et al. (2007, Table 2.1) found that acacia plantations can improve soil water storage capacity and can modify soil structure. For example, the total soil water holding capacity in the 0 – 40 cm depth range under *A. mangium* plantations located in the Jiepai Branch of Wuangxi Gaofeng Forestry Farm, China at age four, seven and eleven years was 2,023 t ha^{-1}; 2,158 t $ha^{-1}$and 2,260.4 t ha^{-1}, respectively and was significantly higher than 1,903 t ha^{-1} of *Cunninghamia lanceolata* plantations aged eighteen years (Table 2.1). In addition, the total water holding capacity of the non-capillary fraction, as an index of water storage in the dry season, was 284.0 t ha^{-1}, 378.6 t ha^{-1} and 421.2 t ha^{-1} that is much higher than *C. lanceolata* plantations of 257.6 t ha^{-1} (Table 2.1). Bin et al. (2007) also reported that soil permeation rate was higher in *A. mangium* than *C. lanceolata*, increasing with stand age and was related to decreasing bulk density and increasing soil organic matter. A comparison of mixed plantations (*Acacia* and three dipterocarpus species including *Dipterocarpus alatus, Hopea odorata and Shorea roxburghii*), soil water content at a depth of 5 cm (in the wet season) was higher in the mixed-planting plot than in the control plot of only dipterocarpus species (Norisada et al. 2005).

Table 2.1 Water holding capacity within 0 – 40 cm depth in different age classes of *Acacia mangium* plantations (Bin et al. 2007)

Species	**Age (yr)**	**Soil depth (cm)**	**Total water storage capacity of non-capillary ($t\ ha^{-1}$)**	**Total water storage capacity ($t\ ha^{-1}$)**	**Total water storage capacity (0 – 40 cm) ($t\ ha^{-1}$)**
C. lanceolata	18	0 – 20	150.0	975.8	
		20 - 40	107.6	928.0	1,903.8
A. mangium	4	0 – 20	190.4	1,057.6	
		20 - 40	93.6	965.4	2,023.0
A. mangium	7	0 – 20	256.2	1,183.8	
		20 - 40	122.4	974.6	2,158.4
A. mangium	11	0 – 20	287.2	1,243.6	
		20 - 40	134.0	1,016.8	2,260.4

Losses of water from soil in plantation systems can occur through both transpiration of plants and evaporation from soil surface (evapotranspiration), soil surface run-off and subsurface run-off (Cienciala et al. 2000, O'Loughlin and Nambiar 2001, Pallardy 2008c, Landsberg and Sands 2010a). Relatively fast canopy closure in acacia plantations (within around 1 yr) tends to result in reduced soil evaporation rate, but higher transpiration rates. *A. mangium* has been reported to have high rates of photosynthesis and transpiration, low water-use efficiency and high moisture content in the stem. This causes a high demand for water and a soil drying rate that is strongly related to tree stocking density, meaning that evapotranspiration is a major factor controlling soil water regimes under acacia plantations (Inagaki et al. 2008).

Soil water availability limits the productivity of forest plantations grown in many environments. Mendham et al. (2011) found that soil water stores always declined under first rotation *Eucalyptus globulus* plantations with different silvicultural practices and in different climate zones in south-western Australia. Plantations with a high stocking density had greater soil water depletion early in the rotation and available soil water was close to zero down to 800 cm for all sites by the end of the rotation. Mendham et al. (2011) used the CABALA model to show that soil water stores in the second rotation are unlikely to be fully replenished under a standard replanting regime. They concluded that the productivity of the second rotation is likely to be lower than that in the first (Mendham et al. 2011).

Water use, water use efficiency and water stress in forest plantations are related to the leaf area index (LAI) and the rate of water vapour transfer from leaves (Battaglia et al. 1998, Drake et al. 2009, White et al. 2010). Drake et al. (2009) found that coppiced *E. globulus* plantations up to age two used more water and drew on stored soil water to a depth of at least 4.5 m while the seedlings had only accessed soil water to a depth of about 90 cm. This was due to above ground biomass and LAI of the coppice being much higher than the seedlings. However, coppice and seedlings showed no significant differences in either their stomatal response to leaf -to-air vapour pressure or intrinsic water use efficiency. Furthermore, CO_2 and light saturated rates of photosynthesis were less in coppice than that in seedlings (Drake et al. 2009). Battaglia et al. (1998) found that LAI of eucalypt plantations declined linearly with water stress.

Reduction of leaf area and litter fall due to water stress occurs through reduced leaf initiation, growth rate and size as well as leaf abscission (Otieno et al. 2005). White et al. (2009) concluded that the level of water stress in thinned *E. globulus* plantations was reduced significantly when subjected to a pre-commercial thinning to 600 trees ha^{-1} while total stand volume at the end of rotation did not decrease compared to un-thinned plantation. Similarly, the water stress of the control treatment was greater than for thinned treatments in thinned and unthinned Black Walnut (*Juglans nigra* L.) plantation (Gauthier and Jacobs 2009). The authors found that this difference in water stress resulted from the fact that soil water content in thinned plots was higher than in the un-thinned plots. For instance, one year after thinning, the thinned trees had an average daily soil water content of 0.29 ± 0.01 m^3 m^{-3} compared with 0.25 ± 0.04 m^3 m^{-3} in control trees (Gauthier and Jacobs 2009).

2.1.3. Nutrients

Kellogg (1950) stated that plants need 15 essential elements for growth. Plants obtain carbon, hydrogen and oxygen from the air. They also need phosphorus, nitrogen, potassium, calcium, magnesium, iron, sulphur and trace amounts of boron, manganese, copper, zinc and molybdenum from the soil (Kellogg 1950). Furthermore, physical and chemical characteristics of a soil plays a crucial role in storage and supply rates of nutrients to plants (Kellogg 1950, Attiwill and Leeper 1987).

Understanding the nutrient cycling in plantation forests is useful in determining necessary nutrients for tree growth during the life cycle of a plantation, and to help maintain nutrient resources in order to support the long-term sustainable productivity of plantations.

The cycle of nutrients in forests is a complex area and research on nutrient cycling has been ongoing since the nineteenth century (Attiwill and Leeper 1987). Attiwill (1993) summarised the general model of nutrient cycling in forests as the following:

(1) Inputs to, and outputs from, the forest;

(2) Transfer of nutrients between plant and soil, including uptake and return to soil by leaching, in litter and root turnover, and by death of individuals;

(3) Internal redistribution of mobile nutrients within the trees.

Nutrient cycling in plantation forests depends on species and their eco-environment. For nitrogen fixing species, nutrient cycles are influenced by the amount of N fixed, the quantity of N and nutrient taken up from the soil, the quantity and quality of litter input to the soil, changing of micro-climate as well as micro-flora and fauna in the soil (Binkley and Giardina 1997). For example, *Casuarina equisetifollia* fixed N at a rate of about 80 kg ha^{-1} y^{-1} whereas legume trees fixed around 100 to 150 kg N ha^{-1} yr^{-1} (Binkley and Giardina 1997) and in 7 year-old *Acacia* stands, N fixation of *A. auriculiformis* was higher than *A. mangium* (Bernhard-Reversat 1996). Nitrogen fixation by *A. auriculiformis* also responded better to P availability compared to *Schima wallichii* and *Castanopnis hystrix* planted in degraded lands in South China (Wang et al. 2010). Nitrogen cycling through litter-fall was high in *Acacia* stands (approximately 170 kg ha^{-1} yr^{-1}, and low in eucalypt and pine stands (ca. 43 kg ha^{-1} yr^{-1}) planted on a poor sandy savannah soil in Congo (Bernhard-Reversat 1996).

The productivity of forests can be increased by adopting suitable silvicultural and nutrient management practices. In recent decades, there has been increasing research in the management of nutrient supply to forests through a variety of practices such as fertilization, legume intercropping, slash and litter retention and other site preparation procedures. Xu and Dell (2003) concluded that optimal nutrient management of eucalypt plantations improved productivity from 10 to 20 m^3 ha^{-1} yr^{-1} in south China. Slash retention at site after harvesting has been shown to increase tree growth because of increased nutrient supplies and a reduction in the loss of soil organic matter after tree planting (Smethurst and Nambiar 1990, Gonçalves et al. 1999, Mendham et al. 2002, Xu and Dell 2003, Sankaran et al. 2004, Gonçalves et al. 2007, Gonçalves et al. 2008a). For example, Smethurst and Nambiar (1990) found that slash, litter and the top 30cm soil in a 37 year-old *Pinus radiata* plantation had 1957 kg N ha^{-1} in which slash and litter accounted for 12 and 25 %, respectively. Likewise, harvest-residue retention increased tree growth of second rotation *Eucalyptus globulus* plantation on at a low fertility grey sand site (Haplic Podzol soil), but had no effect at a high fertility red earth site (Rhodic Ferralsol soil) up to age seven years (Mendham et al. 2002).

Nitrogen (N) has a vital role as a constituent of amino acids: the building blocks of protein. It is found in a variety of other compounds like purines and alkaloids, enzymes, vitamins, hormones, nucleic acids, and nucleotides (Pallardy 2008b). The concentration of N in foliage may account for around 2% of the dry weight in some tree species, and it has essential roles in biochemical and physiological processes because leaf area development and photosynthesis depend on N supply (Kozlowski and Pallardy 1997a, Pallardy 2008b). Foliar nitrogen concentration is used as a key specification to verify seedling conditions for planting. For example, *Eucalyptus globulus* seedlings had optimal growth after planting on mild, ex-pasture sites when foliar nitrogen concentration was 1.5 % (Close 2012).

According to Attiwill and Adams (1993), the total N in surface (0 – 20 cm) soils ranges from 0.8 to 10 t ha^{-1}, of which only a small fraction is required by the trees, while the litter layer of forest soils can contain an additional 100 – 1000 kg N ha^{-1} and can supply a significant proportion of the tree nutrient requirements. In a productive forest, litter may be produced at around 3 to 5 t ha^{-1} per year (up to 10 t ha^{-1} yr^{-1}) with a typical N concentration of 0.5 – 1.0 % (Attiwill and Leeper 1987).

Phosphorus (P) is also an important nutrient in plants and is found in every living plant cell as a part of several key plant structure compounds and as a catalyst in the conversion of numerous key biochemical reactions in plants. This includes energy transfer, photosynthesis, transformation of sugars and starches, nutrient movement within the plant and the transfer of genetic characteristics from one generation to the next (Griffith 2001, Pallardy 2008b). Phosphorus is associated with development of the root system, increased stalk and stem strength, improvement in flower formation and seed production as well as crop quality (Armstrong and Griffin 1999). In particular, P enhances the N- fixing capacity of legume species (Adams et al. 2010). For example, most *A. mangium* provenances show a growth response to P fertiliser (Sun et al. 1992).

Low P availability in soils is one of the principal limitations to tree growth and productivity in temperate, sub-tropical and tropical forests (Vitousek 1982, Attiwill and Adams 1993, Folster and Khanna 1997, Mendham et al. 2002, du Toit 2003, Xu and Dell 2003). The effects of P fertiliser supply on plantations, including increasing tree growth rate at the nursery stage , maintaining sustainable productivity and improving wood quality in plantation forests have been well studied (Sun et al. 1992, Webb et al. 2000, Mendham et al. 2002, Smethurst et al. 2003, Mendham et al. 2004, Wiseman et al. 2009, Mendham et al. 2010, White et al. 2010).

Natural inputs of phosphorus are derived from rock weathering and low atmospheric returns: it is less available in the long-term due to its conversion to recalcitrant organic and adsorbed forms (Walker and Syers 1976). Tropical soils are often strongly P-deficient and moderately deficient for cropping. These soils have a high capacity to rapidly fix applied P due to their low pH and the predominance of ionic forms of Fe and Al and oxides of Fe and Al which lead to the fixation of existing or applied P in the soil and decreased P plant availability (Gonçalves et al. 1997). Low pH and available P in soils are key factors that often result in a P fertiliser response to tree growth in tropical plantation forests. For instance, Xu and Dell (2003) noted that P responses to eucalypt tree growth in the south eastern China were higher than those in the south-western China due to different soil types. Oxisol soils, which are found in the south-eastern areas, have lower pH and available P than the ultisols of south-western China. Phosphorus fertiliser application may be crucial for successive rotations of plantations in tropical soils with low available soil P and high P-fixation capacity (Folster and Khanna 1997)

Phosphorus fertiliser requirements often differ between provenances and species. For example, the response of *A. mangium* to an application of P at 17 weeks in a nursery, affected tree growth and nodulation significantly, but there was no significant difference in growth between two provenances (Sun et al. 1992). However, provenance Ma11 had a stronger response to phosphorus addition than provenance Ma9 and was tolerant of high P supply (Sun et al. 1992). In addition, Webb et al. (2000) found that there were significant differences between four tree species (*Flindersia brayleyana, Castanospermum australe, Cedrela odorata* and *Agathis robusta*) in their growth response to increasing P supply (0, 60, 150, 300 g P tree^{-1} as triple super phosphate 21 % P and 15 % Ca). While there was no height or volume response from two species (*Flindersia brayleyana* and *Castanospermum australe*) to increasing P supply at any age, a response was reported for two other species (*Cedrela odorata* and *Agathis robusta*) at 23 and 31 months after planting. These results are of intrinsic interest to a basic understanding of the diverse nature of nutrient acquisition mechanisms. Some species are able to obtain sufficient P to sustain good growth even when grown in a soil that has low available P.

Ribet and Drevon (1996) found that external P requirements for growth and the efficiency of utilisation of external P were similar for *A. mangium* where it was reliant on N from fixation or from urea. However, shoot growth and the concentration of N and P in leaves were lower in P deficient plants that relied on N_2- fixation than plants that were urea-fed. Phosphorus deficiency also limited nodule growth more than it did shoot growth. Therefore, N_2 fixation in *A. mangium* is quite tolerant to P deficiency (Ribet and Drevon 1996).

2.2. Slash and litter management

2.2.1. Effects of harvest, site preparation, slash and litter management on soil physical properties

In tropical and subtropical plantations the retention of slash and litter after harvesting is a crucial practice to maintain long-term site productivity (Gonçalves et al. 2008a, Nambiar and Kallio 2008). This practice can reduce soil erosion and indirectly soil compaction (Tiarks and Ranger 2008, Rietz 2010, Gonçalves et al. 2013, Titshall et al. 2013). For example, Rietz (2010) combined three harvesting methods (manual, logger and forwarder loaded by a logger) with three types of slash management (broadcast, windrow and slash removal) after harvesting *Eucalyptus grandis* plantations in South Africa. The lowest soil bulk density (BD) was recorded for soils under manual harvest with broadcast retention (1.41 g cm^{-3}) while the highest BD was recorded for soils where the harvesting method used logger and included slash removal (1.66 g cm^{-3}). Titshall et al. (2013) reviewed results from several studies in southern Africa, concluding that retaining slash and litter at the site after harvesting to be a useful management tool to reduce heavy machinery-induced soil compaction. Therefore, a system of minimum heavy machine use combined with retention of slash and litter is recommended for minimising soil erosion and compaction for commercial plantation forest in the tropics and subtropics (Gonçalves et al. 2013).

2.2.2. Effects of slash and litter management on soil chemical properties

Tiarks and Ranger (2008) summarised the effects of site management on soil properties from 16 sites of CIFOR-network projects in eight countries (Table 2.2). The results showed that slash retention at the site did not affect soil organic carbon (SOC) at six sites nor total nitrogen (N) at seven sites. Retaining slash increased SOC at five sites and N at four sites. At some sites effects were more localised, for example, at a site in Brazil, retaining slash increased SOC and soil N in the surface soil to 5 cm during the course of study while no differences in the SOC and N were found in the 5 – 10 cm layer (Gonçalves et al. 2008b). Mendham et al. (2008) indicated that slash treatments did not significantly increase SOC or N at either of two sites with contrasting fertility in Western Australia. SOC increased dramatically from 66 g kg^{-1} to 75 g kg^{-1} up to age 2 yr, in a eucalyptus plantation in South Africa, but there was little change between age 2 and age 7 yr (du Toit et al. 2008) possibly due to surface litter being mixed into the soil or by a difference in sampling methods used (Tiarks and Ranger 2008). Huong et al. (2008) reported that SOC in an *A. auriculiformis* plantation significantly changed in the first two years and then increased over the following two years. Similarly, Xu et al. (2008) found that the SOC in eucalypt plantations in China (Guangdong) changed little initially, and then increased in the following years. The dynamics of SOC in plantations may depend on cultivation practice. For example, SOC decreased from 31.0 to 27.7 g kg^{-1} after nine years under the Chinese fir plantations (Shaohui et al. 2008), possibly due to the multiple cultivations used for weed control or due to variability in soils (Tiarks and Ranger 2008).

Tiarks and Ranger (2008) found that slash retention generally did not tend to measurably increase soil extractable phosphorus (P) due to the relatively small amount of P in slash (e.g. slash contained 9 kg P ha^{-1} in *A. mangium* plantations in Indonesia (Sirega et al. 2008). However, some studies have found differences in soil extractable P. For example, in the surface 10 cm of *Eucalyptus urophylla* plantations increased from 0.7 mg kg^{-1} in the no slash treatment to 1.5 mg kg^{-1} in the double slash treatment, two years after commencing an experiment in Guangdong, China (Xu et al. 2004).

Tiarks and Ranger (2008) concluded that soil pH was not influenced by harvesting and replanting in tropical forest plantations. Similarly, soil exchangeable potassium (K) was not affected by slash retention for almost all sites of the research network except at a site in Brazil, where exchangeable K increased by slash retention from the year of harvesting to age 7 yr. Slash retention had no effect on exchangeable calcium (Ca) or magnesium (Mg) at 10 sites (Table 2.2).

Table 2.2 Impacts of slash and litter retention relative to slash removal on soil chemistry values in the surface 10 cm (data from Tiarks and Ranger 2008).

Country - site	**Species**	**OC**	**Total N**	**Extractable P**	**pH**	**Exchangeable ($cmol_c$ kg^{-1})**		
		g kg^{-1}	**g kg^{-1}**	**mg kg^{-1}**		**K**	**Ca**	**Mg**
Australia								
Busselton	*E. globulus*	↔	↔	↔	↔	↔	↑	↔
Manjimup	*E. globulus*	↔	↔	↔	↔	↔	↑	↑
Queensland	*P. elliottii* x *P. caribaea*	↑	↑	n/a	↓	↔	↔	↑
Brazil								
Itatinga	*E. grandis*	↑	↑	↔	n/a	↑	↔	↔
China								
Guangdong	*E. urophylla*	↔	↔	↑	n/a	↔	↔	↔
Fujian	*C. lanceolata*	↔	↔	n/a	↔	n/a	n/a	n/a
Congo								
Pointe-Noire	*Eucalyptus* hybrid	↔	↔	n/a	n/a	↔	↔	↑
India								
Punalla	*E. tereticornis*	n/a	n/a	n/a	n/a	↔	↔	↔
Surianelli	*E. grandis*	n/a	n/a	n/a	n/a	↔	↔	↔
Vattavada	*E. grandis*	n/a	n/a	n/a	n/a	↔	↔	↔
Kayampoovam	*E. tereticornis*	n/a	n/a	n/a	n/a	↔	↔	↔
Indonesia								
Riau	*A. mangium*	↔	↔	↔	↔	↔	↑	↔
Toman	*A. mangium*	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Sodong	*A. mangium*	↑	↑	↔	↔	↔	↔	↔
South Africa								
KZ-Natal	*E. grandis*	↑	↔	↔	↑	↔	↑	↑
Vietnam								
Binh Duong	*A. auriculiformis*	↑	↑	↔	↑	↔	↔	↔

↑: Concentration increased
↓: Concentration decreased
↔: No significant change
n/a: Data not available

Titshall et al. (2013) reviewed the effects of site management on soil productivity in successive rotations of eucalypt plantations in South Africa. Their review concluded the following:

- Site organic carbon and nutrients may decrease under more extractive harvesting regimes (e.g. off-site debark and whole tree harvesting) and slash and litter management (e.g. broadcasting, windrowing, munching, roller-chopping, burning and removal).
- Removal and/or burning slash and litter resulted in losses of nutrients through soil erosion and leaching.
- The potential impact on the nutrient capital of the site can be estimated based on biomass and harvest residues and the nutrient content in different tree components.

These results have considered current productivity or changes in site condition over a single rotation in South Africa (Titshall et al. 2013). Therefore, Titshall et al. (2013) suggested that future research should focus on response after multiple rotations to test the validity of their findings in order to develop and apply new management practices for sustaining and improving productivity of forest plantations while conserving soil resources.

2.2.3. Tree growth responses to slash and litter management

Results from 16 sites from CIFOR-network projects indicated that the practice of whole tree harvesting negatively affected the growth rates of trees (Nambiar 2008). Nambiar and Kallio (2008) found that retaining slash and litter on site post-harvesting led to an improvement in the productivity of acacias, eucalypts and pine plantations in the next rotation. Gonçalves et al. (2008a) reported a decrease in the productivity of *Eucalyptus* *grandis* (age 6.4 yr) in the second rotation in a Brazilian plantation. The reduction in stem-wood production was greater under the removal of all residues (37 % reduction) than where bark and slash were removed (14.5 % reduction) during harvesting after the first rotation (Gonçalves et al. 2008a) and even higher level of decline has been found in an *Eucalyptus* hybrid in the Congo (Laclau et al. 2010). Whole tree harvesting (total stem, branches and leaves) led to a 21 % reduction in volume compared to harvesting merchantable wood alone in the next rotation (Hardiyanto and Nambiar 2014).

2.3. Stand development and productivity

A comprehensive understanding of the stages of tree growth is important for silviculturists as well as tree growers to understand and apply silvicultural practices that can improve plantation productivity and reduce the time for trees to reach maximum growth rates (Squire et al. 1985). According to Snowdon (2002), there are two basic forms of long term response of plantations to forest management practices. Type 1 responses are characterized by a temporary increase in growth rate that reduces the time needed for the stand to reach a given stage of maturity or stand development. Type 2, responses are characterized by a real and sustained change in stand productivity (Snowdon 2002). Declining productivity with age is a universal phenomenon in plantation forests. For example, Lugo et al. (1988) showed that the mean annual increment of stem wood of *Gmelina arborea* planted in Brazil was 5.25 t ha^{-1} yr^{-1} at age five to seven years but it decreased less than 5 t ha^{-1} yr^{-1} by age nine years. Furthermore, the current annual increment of the *Gmelia arborea* peaked earlier than the MAI at about 8 t ha^{-1} yr^{-1} at age 3.5 yr and it declined rapidly in the following years. This phenomenon can be explained in some situations by a reduction in the supply of natural resources (light, water and nutrients) for tree growth. Ryan et al. (1997) assessed the processes that may result in reduced stand production with age (cited at Binkley et al., 1997, p. 424). They stated the following possible processes may be contributing factors:

- Increasing respiration with accumulation of stand biomass;
- Decreasing nutrient supply with time, leading to greater allocation to root production;
- Reduced photosynthesis owing to increasing resistance to water flow in tall stems;
- Reduced leaf area due to abrasion between tall crowns;
- Increased mortality of older trees;
- Physiological changes associated with aging of tissues;
- Increased reproductive output.

The early phase of growth can be defined as the time to reach maximum leaf area and productivity (Nambiar and Sands 1993, Binkley et al. 1997, Battaglia et al. 1998). This early phase of plantation development can take one year on good sites or up to several years on poorer sites. Productivity tends to peak when trees reach peak leaf area and then it can decline substantially (Binkley et al. 1997). Leaf area index may be one of the most sensitive and integrated measures of stand development. For instance, the productivity of *Eucalyptus globulus* Labill. plantation was strongly related to leaf area, which was in turn influenced by competition from weeds, or defoliation by insects (Nambiar 1990).

A decline in wood productivity has been also observed in many forest plantations after successive rotations of the same species, particularly on low fertility soils. This is associated with a decline in soil fertility, caused by inadequate management, including soil conservation and soil preparation practices that are damaging to soil physical and chemical characteristics, insufficient or imbalanced fertilisation, and inappropriate management of organic residues. The situation is potentially more serious when improved genetic materials are used with a high capacity to extract and assimilate nutrients. Special attention should be given to clonal plantations as they can be very productive and may deplete the soil rapidly without adequate attention to nutrients and residue management practices to sustain their productivity over the long term (Gonçalves et al. 1997).

Plantation productivity in Vietnam:

In Vietnam, acacia plantations are commonly planted on hill-slopes and undulating lands that are not subject to seasonal waterlogging. Volume growth normally observed across the different acacia species planted is in the order *Acacia* hybrid >= *Acacia mangium* > *Acacia crassicarpa* > *Acacia auriculiformis*. The relative growth advantage of *Acacia* hybrid over *Acacia mangium* is less in South than North Vietnam (Kha et al. 2012).

Plantation productivity is inevitably a function of soil depth and fertility, slope, terrain, previous vegetation type and land management, climate, and silvicultural inputs. Table 2.3 shows differences in productivity of acacia plantations under different soil types. A preliminary examination of the relationship between site and potential productivity in Vietnam was done by Sam (2001). He described the following association:

- *North:* On an orthic ferralsol soil at Phu Tho, the MAI of *A. mangium* at age eight years was positively correlated with an increase in soil depth; MAI was 6, 15.7 and 25.7 m^3 ha^{-1} yr^{-1} when the soil depth was < 50, 80, and > 100 cm, respectively. The stand density ranged from 930 to 1100 trees ha^{-1}.

- Central Plateau: On a degraded orthic ferralsol, the MAI of *A. auriculiformis* at age 8 yr was 9 - 10 m^3 $ha^{-1}yr^{-1}$. The low productivity is in part associated with the site being located at higher elevation (800 m).

- South: On a > 100 cm-depth orthic acrisol soil at Bau Bang (Binh Duong province) the MAI of *A. mangium* at age 8 yr was 16 - 22 m^3 $ha^{-1}y^{-1}$; the stand density was 1667 trees ha^{-1}. On a < 50 cm-depth ferric acrisol at Song May (Dong Nai province), the MAI of *A. mangium* at age 8 yr was 15 -19 m^3 $ha^{-1}y^{-1}$; the stand density was 1667 trees ha^{-1}.

On an orthic acrisol soil of > 100 and < 50 cm depth, the MAI of *A. auriculiformis* at age 9.5 yr was 12 - 16 and 6 - 10 m^3 $ha^{-1}yr^{-1}$, respectively. On a fertile acrisol soil, where natural forest had just been cleared, the MAI of *A. auriculiformis* at Phu Tan (Binh Duong province) at age 5.5 yr was 22 - 23.5 m^3 $ha^{-1}yr^{-1}$, and at Minh Duc (Binh Duong province) at age 6 yr was 22 - 25 m^3 $ha^{-1}yr^{-1}$.

On a ferralitic clay-loam at Dong Hoi in Central Vietnam, the MAI of an 871 trees ha^{-1} (un-thinned) stand of selected clones of *Acacia* hybrid at age 4.5 yr was 26.4 m^3 ha^{-1} (Beadle et al. 2013). The mean annual rainfall, temperature and humidity at this site are 2,400 mm, 23.5 ^{o}C and 85 %, respectively. This plantation was severely damaged by a typhoon at age 4.8 y, but the growth trajectory suggests that MAI would have exceeded 30 m^3 $ha^{-1}yr^{-1}$.

This site was used for a thinning experiment. Significant responses to thinning at age 2.5 yr were observed six months after thinning and were sustained for at least two years after thinning. It should be noted that the mean diameter of the un-thinned stand that was established at 1000 trees ha^{-1} was 14.5 cm at age 4.5 yr. If the plantation had been established at >1300 trees ha^{-1}, a stocking density more commonly associated with pulp-wood plantations in Vietnam, the mean diameter would probably have been around 12.1 cm, assuming 100 % survival. These results illustrate the intense intra-species competition that develops at an early age, even in the best-managed plantations, and how this can prejudice individual tree diameter growth.

In general, the growth of all species is greater in South and Central Vietnam than in North Vietnam (Nguyen Hoang Nghia and Le Dinh Kha 1998). In the North, the mean annual height and diameter increments of *A. mangium* on productive sites are around 2 m and 2.5 cm yr^{-1}, respectively; in the South these figures are 2.5 m yr^{-1} and 3.0 cm yr^{-1}, respectively. On productive sites in the South, annual height and diameter increments of *A. auriculiformis* are 2.4 –2.8 m yr^{-1} and 2.5 - 2.8 cm yr^{-1}, respectively for height and diameter. Although seemingly well-adapted to stress, *A. auriculiformis*, tends to perform poorly on dry, low quality sites in Vinh Phu, Quang Tri and Binh Thuan provinces (Nguyen Hoang Nghia and Le Dinh Kha, 1998).

Table 2.3 Soil types and productivity of *Acacia* plantations in Vietnam (Sam 2001).

Location	**Soil types**	**Soil depth (cm)**	**Species**	**Stand age (yr)**	**Stocking (tree ha^{-1})**	**MAI (m^3 ha^{-1}yr^{-1})**
North	Orthic ferralsol	<50	*A. mangium*	8	1100	6
		50 - 80	*A. mangium*	8	1100	15.7
		>100	*A. mangium*	8	1100	25.7
Central	Rhodic ferrasol		*A. auriculiformis*	8	1667	9 - 10
	Rhodic ferrasol		*A. mangium*	8	1667	11
	Rerric acrisol		*A. hybrid*	4.5	871	26.4
	Ferric acrisol	<50	*A. mangium*	8	1667	15 - 19
South	Orthic ferralsol	>100	*A. mangium*	8	1667	16 - 22
	Orthic acrisol	<50	*A. auriculiformis*	9.5	1667	6 - 10
		>100	*A. auriculiformis*	9.5	1667	12 - 16
	Fertile Acrisol	>100	*A. auriculiformis*	5.5 - 6	1667	22 - 25

2.4. Thinning regimes

The overall aim of plantation management is to achieve and maintain optimal growth rates. The adoption of thinning regimes requires information on the impact of a number of factors on productivity. What density of thinning is most appropriate? How old should a plantation be before thinning commences? How often should plantations be thinned? What is the desired final stocking density?

These questions have been explored for some species in tropical and sub-tropical environments (Evans and Turnbull 2004, Smith and Brennan 2006, Cassidy et al. 2012, Glencross et al. 2012, West 2014). In South Africa, to achieve the required mean annual increment of > 30 m^3 $ha^{-1}yr^{-1}$ for *Eucalyptus grandis* plantations, Schonau (1981) suggested the following thinning regimes: (1) Intensity (25 – 58%); (2) Time of first thinning (3 – 7 yr); (3) Thinning frequency (2 – 5 yr); (4) Final stocking (56 – 358 trees ha^{-1}); and (5) Age of clear-felling (15 – 30 yr). From these suggestions it could be concluded that thinning in eucalypt plantations should start when the trees are young, undertaken at frequent intervals, with more intensive thinning when the trees are younger (Schonau and Coetzee 1989). Two thinning applications were applied in eucalypt plantations in New Zealand, where the initial density of trees was greater than 1000 trees ha^{-1}. This management regime was used to improve stand quality (Deadman and Hay 1987). Similarly, thinned from initial planting 1143 and 1430 trees ha^{-1} to final stocking 200 – 300 tree ha^{-1} at age 6 yr (early-age thinning) or age 8 and 9 yr (late-age thinning) was recommended for *Eucalyptus nitens* plantations in Australia due to early-age thinning optimises tree growth rate while later-age thinning maintains and reduces intra-specific competition within stands (Medhurst et al.

2001). This final density would increase growth rate of individual trees during a rotation length of 20 – 25 yr for maximising to use site resources (Medhurst et al. 2001). Messina (1992) stated that thinned of *Eucalyptus regnans* F. Muell. from initial density (1200 trees ha^{-1}) to moderate rate of thinning (350 trees ha^{-1}) to be a suitable final stocking. In Vietnam, low-income smallholders account for over 50% of the domestic wood supply (Beadle et al. 2015) and much shorter rotations for saw-log production will be required to make them an attractive investment. How to rapidly maximise wood yield and value of *Acaci*a hybrid plantations managed for saw-logs therefore needs to be resolved by selecting suitable thinning regimes.

2.5. Growth response to thinning in plantation species

Studies on a range of tropical and temperate tree species have shown that plantations respond differently to thinning depending on tree age at thinning and on the intensity of thinning (Galloway et al. 2001, Medhurst et al. 2001, David 2002, Jaakkola et al. 2006, Comfort et al. 2010).

Medhurst et al. (2001) found that cumulative basal area growth 7 yr after thinning at age 6 yr of an *E. nitens* plantation was unaffected by thinning intensity from initial planting density of 1143 – 1430 tree ha^{-1} down to a density of 300 tree ha^{-1}. When select groups of trees in the thinning treatments were compared with the equivalent groups of trees in the unthinned control, there was a significant response to early-age thinning in the best 100 – 400 trees/ha and to later-age thinning for the best 100 – 600 trees ha^{-1} (Medhurst et al. 2001).

Thinning, pruning and fertiliser applications are often done simultaneously in commercial plantations for sawlogs. The interactive effects of these practices may influence stand structure, light interception and light use efficiency as well as photosynthetic rate (Forrester et al. 2013).

Stem size is a key determinant of log value and can significantly influence harvesting costs, particularly in short-rotation systems. Furthermore, success in the management of plantations of fast growing tropical tree species for the production of large-diameter logs can only be achieved by performing intensive and timely silvicultural intervention. For example, two years after thinning an *Acacia* hybrid plantation, recovery of saw-logs was much higher in the thinned treatment (31.6 %, 300 trees ha^{-1}), compared to the unthinned treatment (6.7 %, 871 trees ha^{-1}) at age 4.5 yr (Beadle et al. 2013).

Reforestation programs in many countries have tended to emphasize plantation establishment, and employ intermediate silvicultural operations such as thinning and pruning (Galloway et al. 2001) to maximise the returns. The aim of these silvicultural interventions is to minimise stem number and maximise stem diameter without sacrificing overall standing volume. In acacia plantations, high planting densities (≥1000 trees ha^{-1}) are required to ensure good apical dominance and stem form, and to minimise branching, so stands need to be thinned to a lower stocking density at a suitable time to maximise the recovery of larger logs (Beadle et al. 2013). To date, however there has been little research conducted on thinning and fertilising acacia plantations to understand the factors that affect tree size and wood quality and quantity to meet requirements for acacia growers, wood processors and consumers.

2.6. Physiological response to management

Photosynthesis is the process by which light energy is captured by plants and used to synthesize reduced carbon compounds from carbon dioxide and water (Kozlowski and Pallardy 1997a, Pallardy 2008a). This process is affected by many environmental factors that to some extent can be manipulated by silvicultural intervention such as thinning, pruning and fertiliser application, which alter the environmental regimes of plants (Kozlowski and Pallardy 1997a, Pallardy 2008a).

The rate of photosynthesis of woody plants varies widely and is influenced by interactions of many environmental and plant factors such as light, temperature, carbon dioxide concentration of the air, water supply, air humidity, soil fertility, salinity, pollutants, chemicals, insects and various interactions among these (Kozlowski and Pallardy 1997a).

Leaves (or phyllodes in the case of acacias) play a vital role in growth and development of woody plants because they are the principal photosynthetic organs (Kozlowski and Pallardy 1997a). Photosynthesis rates vary greatly due to differences in exposure of leaves to light intensity, temperature, CO_2, O_2 availability, water and any factor that influences the production of chlorophyll, enzymes, or energy carriers (ATP and NADPH) (Pallardy 2008a). Light interception and light use efficiency usually key determinants of tree growth which increases linearly with absorbed photosynthetically active radiation up to a critical point (Forrester et al. 2013). Thinning has the potential to increase photosynthetic rate, and light- and water-use efficiencies (Wang et al. 1995, Medhurst and Beadle 2005, Gauthier and Jacobs 2009, Forrester et al. 2012b). Medhurst and Beadle (2005) reported significant increases in light-saturated net photosynthetic rates in the lower and middle crown zones of plantation *Eucalyptus nitens* (Deane & Maiden) Maiden following thinning, and increased foliar nitrogen and phosphorus contents due to a significant decrease in specific leaf area after thinning.

The amount of light intercepted expressed as absorbed photosynthetically active radiation (APAR), and light-use efficiency are among the factors that explain the rate of growth of young trees, with growth tending to increase linearly with APAR (Forrester et al. 2013). Thinning of closed-canopy stands is expected to increase the APAR of retained trees (Wang et al. 1995); hence their higher growth potential (e.g. *B. papyrifera*, Wang et al. 1995; *E. nitens*, Medhurst and Beadle 2005; Forrester et al. 2013). Increases in the amount of available soil moisture following thinning has been associated with a decrease in individual tree water stress because of reductions in stand-level transpiration and losses from rainfall interception (White et al. 2009), and increased water-use efficiency (Forrester et al. 2012b).

The effects of mineral nutrients on photosynthesis are complex and may be both direct and indirect. Increased rates of photosynthesis often, but not always, follow additions of fertiliser to woody plants if nutrients are limiting to growth. The response to fertiliser varies with tree vigour, species, tree age, timing, and composition of fertiliser, stand density, soil fertility, temperature and light conditions (Forrester et al. 2010, Landsberg and Sands 2010a).

Defoliation of trees either artificially or as a result of insect predation can also affect photosynthetic rates. For example, defoliation in eucalypt and pine plantations can increase carbon fixation in the total crown, due to an increase in photosynthetic rates of the remaining foliage of damaged compared to un-damaged plants (Eyles et al. 2011, Quentin et al. 2012). Eyles et al. (2011) found that photosynthetic upregulation in *Pinus radiata* foliage could compensate for losses of up to 35% of the tree crown.

The size and spatial distribution of the canopy have been used to understand that the productivity of plantations can be measured in terms of conversion of light energy into biomass (Beadle 1997). Leave area index (LAI) can be defined as the total one-side area of leaf tissues per unit ground surface area. LAI is a key driver of water and nutrient use, carbon balance and the rate of growth of plantation forests. However, these interactions can be environmentally dependent and how much is intercepted is determined by a plant's leaf area index (LAI) (Landsberg and Sands 2010b). Positive relationships are observed between LAI and biomass production (Beadle et al. 1982, Smethurst et al. 2003). Reductions in LAI are determined by the intensity of thinning, but rates of increase of LAI may be independent of residual stocking; however residual stocking can have a strong effect on leaf area increase per tree which is correlated with changes in crown length (Medhurst and Beadle 2001). A contributory factor in this recovery of LAI is a reduction in litterfall production which decreases with thinning intensity and resulted in a significant relationship between annual litterfall and basal area in thinned *A. mangium* plantations (Kunhamu et al. 2009).

Although there are many studies that have explored the effect of thinning of *Eucalyptus nitens* and *Eucalyptus globulus* plantation on tree growth and physiological responses, (Battaglia et al. 1996, Battaglia et al. 1998, Pinkard et al. 1998, Medhurst et al. 2002, Medhurst and Beadle 2005, Forrester et al. 2012b), research on physiology of acacia plantations is limited and there has been no reported studies on the physiological response of *A. auriculiformis* plantations to thinning in the scientific literature.

2.7. Hypothesis

Overarching hypothesis: That yield and returns from tropical acacia plantations can be improved by managing water and nutrients, particularly during the inter-rotation and at thinning time.

Specific hypotheses to be tested in this project:

- During the inter-rotation, conserving organic matter and nutrients will maintain and improve productivity in successive rotations of *A. auriculiformis* plantations as well as prevent reduction in site-level soil organic carbon and nutrients.

- At mid-rotation thinning, conserving organic matter and nutrients through slash retention, in addition to phosphorus fertiliser application, will enable the use of nutrient and light resources to optimise sawlog production.

- Increasing the intensity of thinning reduces individual tree water stress, which extends the daily growth phase and lengthens the growing season in the dry season on water-limited sites, enhances the photosynthetic capacity, water use efficiency and light-use efficiency of the stand, and allows the trees to maintain deeper canopies.

- Early thinning (at or near canopy closure) when the trees are still rapidly growing leads to larger thinning responses and greater stand volume recovery than late thinning (at least one year after canopy closure) on sites that are water limited in the dry season.

Chapter 3. Improving productivity and sustainability of successive rotations of *Acacia auriculiformis* plantations in South Vietnam

Vu Dinh Huong[1,3,4*], E. K. Sadanandan Nambiar[2], Le Thanh Quang[1], Daniel S. Mendham[3], Pham The Dung[1]

[1] Forest Science Institute of South Vietnam, 01 Pham Van Hai Street, Tan Binh District, Ho Chi Minh City, Vietnam.

[2] CSIRO Land and Water, Canberra, ACT 2601, Australia.

[3] CSIRO Land and Water, Private Bag 12, Hobart, Tasmania 7001, Australia.

[4] School of Land and Food, University of Tasmania, Private Bag 98, Hobart, TAS 7001, Australia.

[*] Corresponding author: Huong.VuDinh@utas.edu.au

This chapter has been published in Southern Forests 2015, 77 (1): 51-58.

Abstract

We studied the productivity of *A. auriculiformis* plantations in South Vietnam over three successive rotations covering 15 years. The focus of our study was on the effects of inter-rotation management on stand growth and soil properties. Contrasting slash and litter management treatments were applied at the start of the second rotation, and re-applied at the start of the third rotation with an additional phosphorus fertilizer treatment. There were improvements in the genetics of planting stock, weed control and stocking with each rotation. Average growth rates (MAI) increased from 10.6 $m^3\ ha^{-1}\ yr^{-1}$ in the first rotation (age 7 yr) to 28.3 $m^3\ ha^{-1}\ yr^{-1}$ in the second rotation (age 6 yr) and to 33.9 $m^3\ ha^{-1}\ yr^{-1}$ at age 5 yr in the third rotation. Removal of slash and litter after harvesting the first rotation removed 20.2 Mg ha^{-1} biomass, containing 169.6, 13.9, 76.3, and 25.1 kg ha^{-1} of N, P, K, and Ca, respectively, from the site. Greater amounts were removed after the second rotation commensurate with higher amounts of biomass produced. Slash and litter removal reduced growth of the second rotation by 13% compared to their retention. Soil organic carbon in the 0-10 cm soil layer increased from 16.7 g kg^{-1} at the end of the first rotation to 22.8 g kg^{-1} at the end of the second with a corresponding increase in soil nitrogen from 1.2 g kg^{-1} to 1.7 g kg^{-1}. Over the same time, soil organic carbon and nitrogen contents were 26% and 40% greater, respectively in treatments with slash and litter retained compared to initial levels before treatment application. In the second rotation, there was no growth response to P fertilizer but extractable soil P declined during this period. In the third rotation there was a response to added P. Overall results demonstrate that there is an opportunity to increase and sustain production of *A. auriculiformis* over at least three rotations by integrated

management practices promoting better stocking, planting of genetically improved stock, organic matter and nutrient conservation and judicious weed management.

Keywords: Tropical plantations, site management, harvests, inter-rotation, soil carbon and nutrients.

3.1. Introduction

Vietnam had established an estimated 1.1 M ha of acacia plantations by 2013, consisting of 600 000 ha of *Acacia mangium*, 90 000 ha of *Acacia auriculiformis* and 400 000 ha of *Acacia* hybrid (Nambiar and Harwood 2014). These resources, managed in rotations of 5 to 8 yr, are important contributors to the rural economy, through supporting a wood chip export and local furniture industries (Kien et al. 2014). *A. auriculiformis* is preferred by some growers because of its higher density and appearance properties. It fetches higher price for furniture making than other acacias and is also suitable for pulp. It is mostly grown in central and southern Vietnam on land cleared of degraded native vegetation. The growth rates are highly variable, ranging between 10 and 25 m^3 ha^{-1} yr^{-1}, depending on sites (Forest Science Institute of Vietnam 2010). Harvesting of first-rotation acacia plantations began in the 1990s and the areas under successive rotations are increasing (Phat 2011). Access to new land for forestry is limited, especially in the south, and the growing opportunities for a wood-based economy can only be realized by increasing and sustaining production from the current land base.

For the sustained productivity of short rotation forest crops in tropical environments, the inter-rotation management phase (including practices such as harvesting, site management and establishment of the next rotation) is a critical one, that carries risks as well as opportunities (Nambiar and Harwood 2014). For example, harvesting intensity and subsequent management of organic matter and nutrients at sites can have significant impacts on soil and productivity (Nambiar and Kallio 2008, Laclau et al. 2010, Gonçalves et al. 2013, Nambiar and Harwood 2014). A loss in productivity of 21% was observed in *A.*

mangium in South Sumatra after applying whole tree harvesting treatment compared to slash and litter retention (Hardiyanto and Nambiar 2014). Even higher levels of impacts on growth have been reported for *Eucalyptus grandis* in Brazil (Gonçalves et al. 2008a) and *Eucalyptus* hybrids in the Congo (Laclau et al. 2010). The potential effects of harvesting and site management on soil properties at a range of sites have been summarized in a review (Nambiar and Harwood 2014).

While there has been significant research on genetic improvement of acacias in Vietnam (Kha 2001, Hai et al. 2008, Kha et al. 2012), there has been much less aimed at understanding and managing for sustainable production over multiple rotations. This prompted in 2001/2002 the first long-term study in Vietnam on the sustainable production *A. auriculiformis* as a part of an international network project on tropical plantations (Huong et al. 2008, Nambiar 2008). In this paper, we report on results from the full second rotation and up to age five years into the third rotation. The specific objectives were to: (1) quantify the biomass and nutrient export under contrasting harvesting and site management regimes; (2) assess their impacts on soil properties and (3) investigate the trends in productivity across three consecutive rotations.

3.2. Materials and Methods

3.2.1. Location, climate and soils

The site was located at the Phu Binh station, Binh Duong Province (11.3° N, 106.8° E). The region has a mean annual temperature of 26.6°C, average rainfall of 2 487 mm yr^{-1}, with a dry season typically from December to April.

The soil type is a Chromic Acrisol, with a sandy clay loam A horizon, grading to a sandy clay B horizon. Key soil properties in the 0 -10 cm horizon are: clay 17.7 (± 1.5) %, $pH_{(H20)}$ 4.8 (± 0.2), $pH_{(KCl)}$ 4.0 (± 0.2), soil organic carbon (SOC) 16.7 (± 0.1) g kg^{-1}, total nitrogen (N) 1.2 (± 0.01) g kg^{-1} and $Bray^{-1}$ extractable phosphorus (P) 10.8 (± 0.6) mg kg^{-1}.

3.2.2. First rotation

The site was under degraded native vegetation before conversion to plantation. Vegetation was cleared with a bulldozer, biomass was burnt and then ploughed twice. Seedlings of *A. auriculiformis* (unknown seed origin) were planted in July 1995 at spacing of 3 × 4 m (833 trees ha^{-1}). The stand was hand weeded and ploughed twice per year between tree rows for weed control during the first three years. By the end of the rotation, the understorey vegetation was high, and dominated by shrubs and grasses.

The stand was harvested manually at age seven years. Experimental plots were established before harvesting, when diameters at breast height (DBH at 1.3 m) of all trees in the plots were measured. Selected trees were sampled for biomass estimation and soil samples taken (see details later).

Litter on the forest floor and understorey vegetation was assessed by sampling all biomass within four randomly located quadrats (1 m^2) per plot. Litter was separated into leaf, branches, stem wood and bark, and reproductive parts. The understorey was separated into woody and non-woody plants. These components were weighed and sub-samples from each were oven-dried at 76°C to a constant weight. Sub-samples of the dried samples were ground and used for nutrient analysis.

3.2.3. Second rotation (Slash and litter management)

The treatments applied before planting of the second rotation were:

BL_0 All aboveground biomass including the crop trees, understorey and litter removed from the plots.

BL_1 Stem wood with bark harvested, all slash and litter retained with minimum soil disturbance.

BL_2 Stem wood with bark harvested. The same as in BL_1 but slash alone from BL_0 plots was brought in and distributed evenly over the existing slash (Double slash).

The experiment was a randomized complete block design with five replications and three treatments. Seedlings were raised from seeds collected from a regional seed orchard consisting of selected provenances. After slash and litter treatments were applied, seedlings were planted into individual pits at a spacing of 3 × 2 m (1666 trees ha^{-1}), and 50 g of 16-16-8 NPK fertilizer was applied per tree. Each plot was 1152 m^2 (12 rows×16 trees row^{-1}), and had two buffer rows giving 96 trees in the net measured plots. An additional plot, treated as $BL_{1,}$ with 1 250 trees was set up for sequential biomass harvesting. Weeds were controlled in the first two years by applying 1.9 kg ha^{-1} glyphosate, twice per year. The stand was harvested at age six years.

3.2.4. Third rotation

After harvesting the second rotation manually, the BL_0 and BL_1 treatments were reapplied as before. However, the previous BL_2 plots were treated as BL_1 and received one application of superphosphate fertilizer at 20 g $tree^{-1}$ P (30 kg ha^{-1} P). This treatment is referred to as BL_1+ P. There were no other fertilizers applied at planting. This treatment was introduced because of evidence of decline in extractable soil P and to test the response to P application. The site was planted with a mixture of clones AA1 and AA9 (Nghia et al. 2010). Weeds were controlled as before.

3.2.5. Tree growth measurement

Tree DBH was measured annually. Tree heights at the final measure were estimated by using equations 3.1-3, derived from destructive sampling:

(3.1) First rotation: Y = 14.53 log X – 1.13 (R^2 = 0.92, *n* = 30) at age 7 yr;

(3.2) Second rotation: Y = 24.54 log X -10.25 (R^2 = 0.71, *n* = 60) at age 6 yr;

(3.3) Third rotation: Y = 18.42 log X – 0.95 (R^2 = 0.83, *n* = 15) at age 5 yr

where Y is tree height in m, and X is DBH in cm.

Standing volume was calculated by:

(3.4) $$V = \pi \left(\frac{D}{200}\right)^2 * H * F$$

where *V* is standing volume in m^3, D is DBH in cm, H is total height in m and F is a form factor (F = 0.475). These equations were developed by felling and assessing 210 trees across the three rotations. A common volume equation was used across the rotations because the form factor was not significantly different between rotations (tested using rotation as a grouping factor in the regression analysis).

3.2.6. Estimates of biomass and nutrients

Trees, representative of the range of diameter classes were destructively sampled: 30 at age 7 yr of the first and 15 at age 6 yr of the second rotation. After felling, DBH and stem length (to a top end diameter of 3 cm) were measured. The stem was divided into five equal length sections; wood and bark in each section were weighed and subsamples were used for dry mass determination. Branches and foliage were treated similarly. Allometric regression relationships between DBH (X) and stem plus bark, and branch (< 1 cm, 1 - 5 cm, and > 5 cm) biomass (Ys) were established by using the exponential model:

(3.5) $Y= aX^b$ where a and b are coefficients.

Estimates of stem-wood mass required the addition of a linear component to the model:

(3.6) $Y = 13.34\ X^{1.22} - 19.49\ X$ ($R^2 = 0.96$, $n = 120$).

An exponential model for estimating foliage biomass did not fit the data as well as it did for other components because trees had an increasingly higher cumulative diameter with age, but green phyllodes are not retained on trees because they senesce and fall. A linear function with an age modifier (A) provided better fit and a more accurate estimation:

(3.7) $Y = 0.62\ X - 1.12 - 0.64\ A$ ($R^2 = 0.71$, $n = 210$).

Biomass components were estimated at the plot level by applying the regression to individual trees and summing to give plot totals. In this paper, only the biomass estimates at the end of the first and second rotations are reported. All data on biomass in this paper refers to dry mass.

Six trees representing the distribution of DBH classes were sub-sampled for the biomass components. Samples were ground to ≤ 0.02 mm fraction and used for nutrient analyses.

Samples of biomass and litter were digested in concentrated sulphuric acid and 30% hydrogen peroxide (Lowther 1980) and all nutrients were measured from that digest according to methods adapted by Forest Science Institute of South Vietnam: N- Kjeldahl; P- spectrophotometer; K- flame photometer; and Ca - atomic absorption spectrometer. The nutrient concentrations were multiplied by mass to estimate contents.

3.2.7. Litterfall

In the second rotation, litterfall was collected fortnightly between ages two and four years from five litter traps (each 1 m^2) per plot in the BL_1 treatment. Litter was dried to constant weight at 76°C, separated into leaf, twigs and other components, and weighed. Nutrients were analysed as above.

3.2.8. Soil sampling and analysis

In the second rotation, soil samples were collected annually in July. Soil cores (0 - 10 cm, 10 - 20 cm soil depth) were taken, excluding the litter, from five locations in each plot, bulked within depths per plot, air-dried, sieved and fractions < 2 mm were analysed. Soil pH, Soil organic matter (SOC), N, extractable P and cation exchange capacity (CEC) were measured according to van Reewijk (2002). Soil bulk density was determined on undisturbed soil cores, using one sample from each plot at 0 - 10 and 10 - 20 cm depth.

3.2.9. Statistical analysis

One-way ANOVA was used to test for treatment effects on soil and tree growth at each measure/sampling time. Least significant difference (LSD) in a multiple range test (Turkey

HSD) was used to test the significant difference between means. In the text, the standard errors of the mean are given in the brackets. Statistical testing was conducted with Genstat 13th Edition (VSN International 2011).

3.3. Results

3.3.1. Impacts of harvesting intensity on organic matter and nutrients at the site

In the first rotation, the total standing biomass was 53.4 Mg ha^{-1}, comprising stem wood (70%), bark (8%), branches (19%) and foliage (3%) (Table 3.1). Litter and understorey together was 8.1 Mg ha^{-1}, litter (63%) and understorey (37%). In the second rotation, total standing biomass and litter in the BL_1 treatment were 109.1 Mg ha^{-1} and 4.3 Mg ha^{-1}, respectively; the total nutrient contents were 554.5 kg ha^{-1} N, 80.6 kg ha^{-1} P, 258.9 kg ha^{-1} K and 72.7 kg ha^{-1} Ca (Table 3.1). The biomass and the nutrient content of the second rotation was approximately double that of the first rotation.

Quantities of organic matter and nutrients removed from a site are dependent on harvesting intensity. For example, at the end of the first rotation when whole trees, litter and under-storey were removed (BL_0) the amounts exported were large: 284.8 kg ha^{-1} N; 42.9 kg ha^{-1} P; 157.8 kg ha^{-1} K and 46.9 kg ha^{-1} Ca. When only merchantable wood with bark was removed (BL_1), fewer nutrients were removed: 115.2 kg ha^{-1} N; 29.0 kg ha^{-1} P; 81.5 kg ha^{-1} K and 21.8 kg ha^{-1} Ca. Thus under BL_1 regime more nutrients were retained: 169.6 kg ha^{-1} N; 13.9 kg ha^{-1} P; 76.3 kg ha^{-1} K and 25.1 kg ha^{-1} Ca. Removal of slash and litter at the end of the second rotation resulted in doubling of nutrient depletion compared to the first rotation because of the corresponding increase in biomass (Table 3.1). Table 3.2

summarizes the net amounts of biomass and nutrients remaining in the slash and litter retained treatments (including the understory) at the end of the first and second rotations.

Table 3.1 Above-ground biomass and nutrient content of the *A. auriculiformis* plantation at the end of the first (1R) and second (2R) rotations

Components	Dry mass ($Mg\ ha^{-1}$)		Nutrient content ($kg\ ha^{-1}$)							
			N		P		K		Ca	
	1 R	2 R	1 R	2 R	1 R	2 R	1 R	2 R	1 R	2 R
Live biomass (trees)										
Stem wood	37.1	75.8	59.0	135.2	24.5	47.3	59.8	115.3	8.2	15.7
Bark	4.2	8.4	56.2	121.3	4.5	8.4	21.7	40.3	13.6	25.4
Branches	10.4	20.4	51.5	144.8	8.6	15.7	28.6	52.2	12.5	23.0
Leaves	1.7	4.5	39.8	111.1	3.1	8.0	13.6	35.0	2.5	6.5
sub-total	*53.4*	*109.1*	*206.6*	*512.4*	*40.7*	*79.4*	*123.6*	*242.8*	*36.9*	*70.6*
Litter	5.1	4.0	50.6	39.6	1.0	1.1	17.8	14.8	8.5	1.9
Understorey	3.0	0.3	27.6	2.5	1.2	0.1	16.4	1.3	1.5	0.2
sub-total	*8.1*	*4.3*	*78.2*	*42.1*	*2.2*	*1.2*	*34.2*	*16.1*	*10.0*	*2.1*
Total	61.5	113.4	284.8	554.5	42.9	80.6	157.8	258.9	46.9	72.7

Table 3.2 Treatment effects on slash and litter biomass and nutrients retained at site at the end of the first and second rotations

Treatment	Dry mass	Nutrient (kg ha^{-1}) [1]			
	(Mg ha^{-1})	N	P	K	Ca
At the end of the first rotation					
BL_1	20.2	169.6	13.9	76.3	25.1
BL_2	40.7	330.9	26.7	148.8	48.7
At the end of the second rotation					
BL_1	29.1	294.0	24.8	102.2	31.1
BL_1 +P	32.6	330.4	27.9	114.8	35.0

[1] The nutrient content includes that in the litter and understorey vegetation

3.3.2. Effects of slash and litter management on soil properties in the second rotation

3.3.2.1. Soil bulk density

At the end of the first rotation, the soil bulk density at 0-10 cm depth was 1.41 (± 0.01) g cm^{-3} and at 10 - 20 cm it was 1.56 (± 0.01) g cm^{-3}. At the end of second rotation, respective values at 0 - 10 cm for BL_0, BL_1, BL_2 treatments were 1.33 (± 0.01) g cm^{-3}; 1.30 (± 0.02) g cm^{-3} and 1.24 (± 0.02) g cm^{-3}, and at 10 - 20 cm, 1.38 (± 0.01) g cm^{-3}; 1.36 (± 0.01) g cm^{-3} and 1.33 (± 0.02) g cm^{-3}. There was an overall decrease in bulk density from the start to end of the second rotation.

3.3.2.2. Soil pH

There were no significant differences in pH between pre-harvest of the first rotation and the end of the second rotation (Data not presented). Similarly, there were no significant differences due to treatment through all years. Soil pH $_{(H2O)}$ fluctuated between 4.5 (± 0.05) and 4.9 (± 0.05) in all treatments and there was no difference between 0 - 10 cm and 10 - 20 cm depth. Soil pH $_{(KCl)}$ was lower ranging between 3.7 (± 0.02) and 4.0 (± 0.02) and also did not show any significant changes over time.

3.3.2.3. Exchangeable cations

At the end of the second rotation, in the 0 - 10 cm soil layer, slash and litter retention resulted in a small increase in exchangeable K, 0.30 (± 0.02) $cmol_c\ kg^{-1}$ compared to 0.26 ± 0.01 $cmol_c\ kg^{-1}$ when slash and litter removed and the pre-treatment value of 0.27 (± 0.02) $cmol_c\ kg^{-1}$. The initial exchangeable Ca was 0.55 (± 0.03) $cmol_c\ kg^{-1}$ which decreased over to the rotation in BL_0, BL_1 and BL_2 treatments to 0.41 (± 0.01), 0.44 (± 0.01) and 0.46 (± 0.01) $cmol_c\ kg^{-1}$, respectively. Similarly, exchangeable Mg declined from an initial value of 0.30 (± 0.01) $cmol_c\ kg^{-1}$ to 0.24 (± 0.01), 0.25 (± 0.01) and 0.27 (± 0.02) $cmol_c\ kg^{-1}$ in BL_0, BL_1 and BL_2 treatments, respectively. There were no statistically significant differences between any treatments.

3.3.2.4. Changes in soil organic carbon and nitrogen during the second rotation

Soil organic carbon content declined slightly after planting, from 23.5 (± 0.4) Mg ha^{-1} to 21.6 (± 0.3) Mg ha^{-1} at age one year. Soil carbon content increased consistently thereafter, both with slash and litter retention and stand age (Figure 3.1a), even after accounting for the decline in soil bulk density over time. The differences between treatments were significant ($p < 0.05$) from age three years. The net increases in SOC content over the rotation period compared to initial level in treatments BL_0, BL_1 and BL_2 were 14, 26 and 37%, respectively, (Figure 3.1a). Because of the declining bulk density, less of the originally assessed 0 - 10 cm depth range would have been sampled subsequently, so the amounts in Figure 3.1 are underestimates of the SOC and N gain for a depth equivalent to the same mass of the initial soil samples at the end of the first rotation. Soil N followed the same trends as SOC (Figure 3.1b). At the start of the second rotation, the 0-10 cm soil had 1.57 (± 0.04) Mg ha^{-1} N. Six years later, the amounts in BL_0, BL_1 and BL_2 were 2.02 (± 0.03), 2.20 (± 0.05) and 2.40 (± 0.07) Mg ha^{-1} N, respectively.

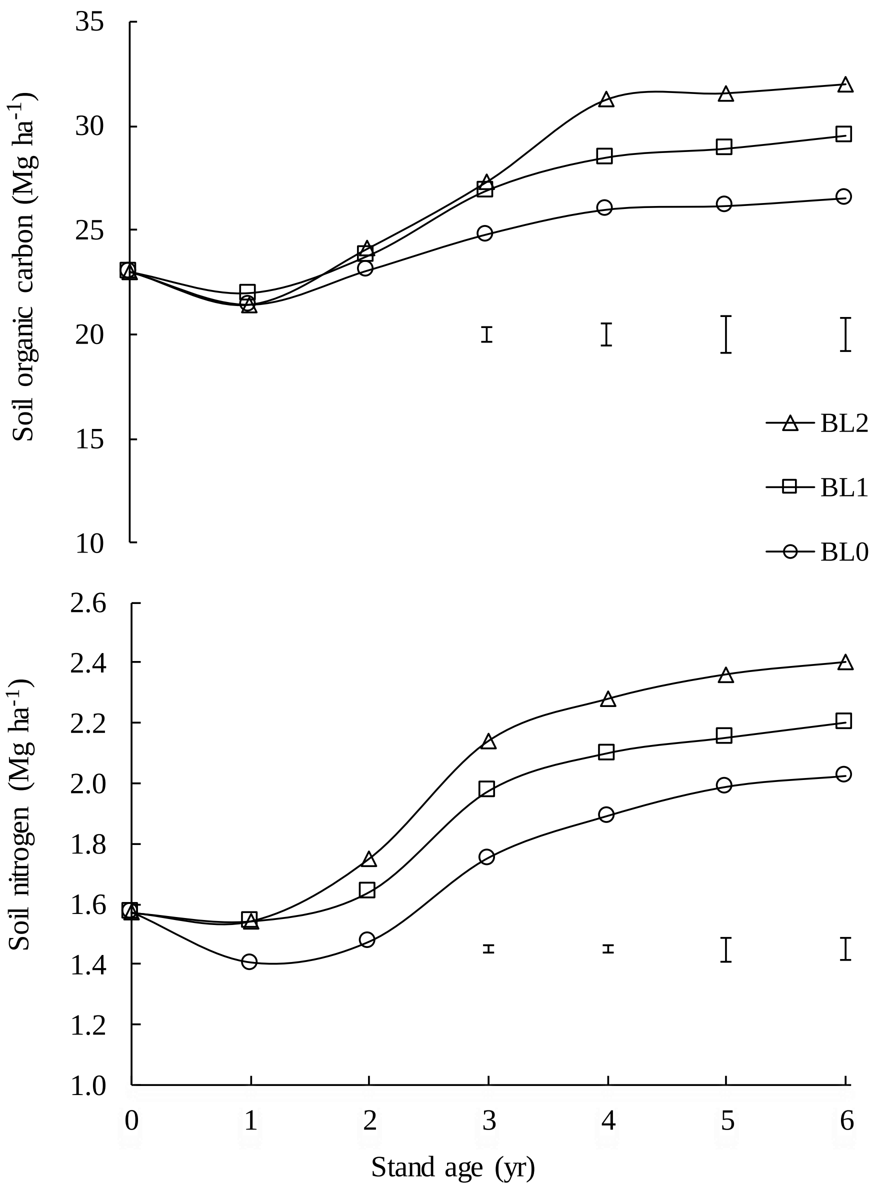

Figure 3.1 Soil organic carbon and nitrogen (0 - 10 cm soil layer) from the end of the first rotation to the end of the second at age six years in an *A. auriculiformis* plantation. Vertical bars in the figure indicate LSDs at $P < 0.05$. Note: BL_0: All slash and litter removed, BL_1: Slash retained and BL_2: Double slash.

3.3.2.5. Soil phosphorus

There were no differences in extractable soil phosphorus (P) content between the BL_0 and BL_1 treatments, but the double slash treatment (BL_2) did result in a small but consistent increase (Figure 3.2). Soil extractable P in all the treatments decreased from a mean value of 12.8 (± 0.4) kg ha^{-1} at age one year to a mean value of 7.4 (± 0.3) kg ha^{-1} at age three years and then remained stable until age six years (Figure 3.2). In contrast, the amounts of P in the trees (excluding litter) increased from 4.3 kg ha^{-1} at age one year to 44.9 and 79.4 kg ha^{-1} at age three and six years, respectively.

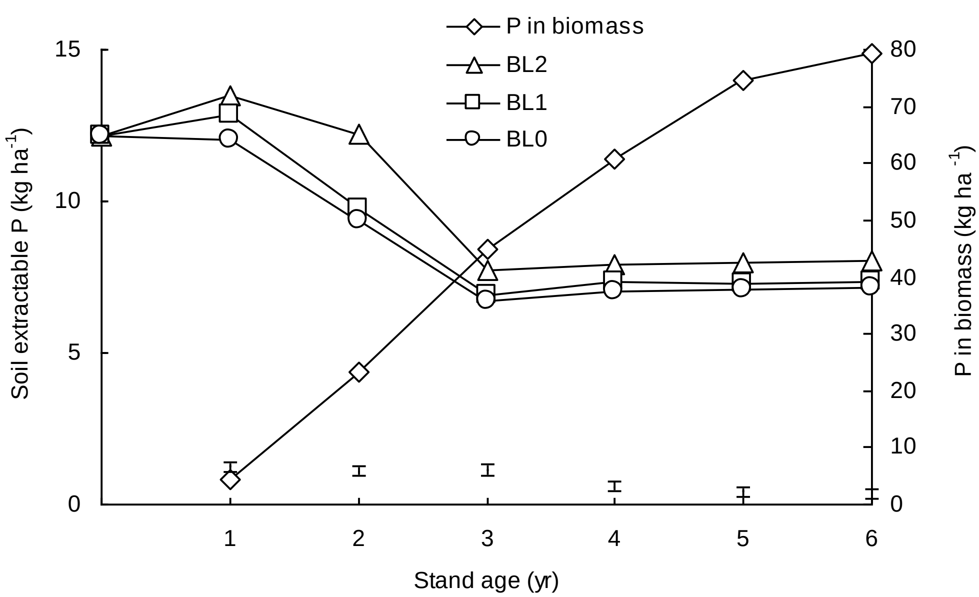

Figure 3.2 Extractable phosphorus (0 - 10 cm soil layer) and phosphorus in above-ground biomass of the *A. auriculiformis* plantation from age one to six years of the second rotation. Vertical bars in the figure are LSDs at $P < 0.05$ for soil extractable P.

3.3.3. Litterfall

Litterfall and nutrient contents were measured from age two (when litterfall began) to age four years. Rates were higher in the dry seasons than in wet seasons. The rates were not significantly different between years. The mean rates of litter fall and nutrients in them were: 6.5 Mg ha^{-1} yr^{-1} mass, 83.1 kg ha^{-1} yr^{-1} N, 2.2 kg ha^{-1} yr^{-1} P, 29.4 kg ha^{-1} yr^{-1} K and 5.4 kg ha^{-1} yr^{-1} Ca.

3.3.4. Effects of slash and litter management on stand growth

Tree survival was unaffected by treatment; mean value was 87%. Both height and stem diameter increased with slash and litter retention (Table 3.3), and statistically significant increases were found between BL_0 (all slash and litter removed) and BL_2 (double slash) treatments which resulted in an increased stem volume of 20.7% over BL_0. The mean volume in the BL_1 and BL_2 treatments was 13.1% higher than that in the BL_0 treatment.

Table 3.3 Effects of slash and litter retention treatments on stand growth at age six years of the second rotation. Different letters indicate means are significantly different at $P < 0.05$.

Treatments	Height (m)	DBH (cm)	Volume ($m^3\ ha^{-1}$)	MAI ($m^3\ ha^{-1} yr^{-1}$)
BL_0 (All slash and litter removed)	16.7^a	12.8^a	160.8^a	26.8
BL_1 (Slash retained)	17.1^{ab}	13.2^{ab}	169.7^a	28.3
BL_2 (Double slash)	17.4^b	13.6^b	194.1^b	32.4
P-value	0.03	0.04	<0.01	
LSD (*p=0.05*)	0.5	0.6	17.5	

In the third rotation at age five years, survival was 95% and not affected by treatment. The removal of slash and litter in the third rotation reduced volume by 7.8% compared to the BL_1 treatment. The BL_1+P treatment improved volume by 9.6% over BL_1 and 18.1% over BL_0 (Table 3.4).

Table 3.4 Effects of slash and litter retention and phosphorus fertilizer application on stand growth at age five years of the third rotation. Different letters indicate means are significantly different at $P < 0.05$.

Treatments	Height (m)	DBH (cm)	Volume (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})
BL_0 (All slash and litter removed)	18.8[a]	12.0[a]	157.2[a]	31.4
BL_1 (Slash retained)	19.0[ab]	12.2[ab]	169.4[b]	33.9
BL_1 + P (Slash retained + 30 kg ha^{-1} P)	19.3[b]	12.6[b]	185.6[c]	37.1
P-value	0.02	0.03	<0.01	
LSD (p=0.05)	0.3	0.4	10.2	

3.3.5. Productivity of three successive rotations

The stocking rates at the final measure of the first, second and third rotations were 658, 1400 and 1492 trees ha^{-1}, and productivity (MAI) was 10.6, 28.3 and 33.9 m^3 ha^{-1} yr^{-1}, respectively (Table 3.5). There was more than 2-fold increase in productivity from first to second rotation and a further increase in the third rotation. For second and third rotations these results (averaged across treatments) illustrate substantial potential for productivity increases with improved management. Higher growth rates in the second and third rotations compared to the first are in a large measure attributable to higher stocking and survival, but also to improvements in management including deployment of genetically improved of planting stock and timely weed control. The growth in the BL_0 plots in the second and third rotations (Tables 3.3 and 3.4) were higher than that in the first rotation (Table 3.5), highlighting the importance of genotype and management for attaining higher productivity.

Table 3.5 Productivity of three successive rotations of *A. auriculiformis* in South Vietnam.

Items	First rotation	Second rotation[(1)]	Third rotation[(1)]
Stand age (yr)	7	6	5
Trees at planting (trees ha^{-1})	833	1666	1666
Tree at harvest (trees ha^{-1})	658	1400	1492
Survival rate (%)	79	84	90
Total standing volume (m^3 ha^{-1})	74.3	169.7	169.4
MAI (m^3 ha^{-1} yr^{-1})	10.6	28.3	33.9

[(1)] Second and third rotations used single slash treatment (BL_1) for productivity comparison.

3.4. Discussion

Export of biomass and nutrients in harvested wood is unavoidable in commercial forestry, but there are ways to minimize the depletion of organic matter and nutrients from sites. For example, at the end of the second rotation, debarking and distributing bark at the site would retain: 121.3 kg ha^{-1} N, 8.4 kg ha^{-1} P, 40.3 kg ha^{-1} K and 25.4 kg ha^{-1} Ca. The amount of P removed in debarked merchantable wood would have been 47.3 kg ha^{-1}, but the P in other components (bark, slash and litter + understorey: 8.4 kg ha^{-1}, 23.7 kg ha^{-1} and 1.2 kg ha^{-1}, respectively) can be retained, which is likely to be important given the observed response to added P in the third rotation (Table 3.4). Conservation of organic matter and nutrients increased growth in both second and third rotations (Tables 3.3 and 3.4); conversely, removal of slash decreased productivity.

These results are similar to those found for *Acacia mangium* plantations in Sumatra, where slash retention increased volume by 21 % compared to slash removal (Hardiyanto and Wicaksono 2008). Similarly, with *Eucalyptus grandis* in Brazil, removal of slash and litter resulted in a 37% decline in productivity (Gonçalves et al. 2008) and even higher level of decline has been found in a *Eucalyptus* hybrid in the Congo (Laclau et al. 2010). A review of results from tropical and subtropical experiments using a range of fast-growing plantation species found a 10 - 60% decline in production induced by poor inter-rotation management practices, including the removal of slash and litter between rotations (Nambiar and Harwood 2014).

Soil pH showed no significant changes over time or with treatment. This is similar to the results from *Acacia mangium* sites in Indonesia (Sirega et al. 2008, Hardiyanto and Nambiar 2014) and *Eucalyptus globulus* in Western Australia (Mendham et al. 2008). However, some studies in Vietnamese soils based on chronosequence data have shown in some situations that acacia plantations are associated with a minor decrease in soil pH (Sang et al. 2012, Dong et al. 2014). Nambiar and Harwood (2014) reviewed results from several studies with short rotation acacia plantations and concluded that results based on chronosequence data were confounded by site history and sampling errors (e.g. single measurement of a dynamic property) and are questionable. That review concluded that soil pH can be maintained with proper site management in short rotation plantations including acacias. The small decline in exchangeable cations observed over time in our study was also reported by Hardiyanto and Nambiar (2014) and may have been partly associated with leaching through the surface layers and partly with uptake by trees although this effect was mitigated by retention of slash and litter. The amount of extractable P at the end of the first rotation was low, 12.1 kg ha^{-1}, and declined further during the second rotation (Figure 3.2), although P was recycled through both litterfall and the decomposing slash. However, application of P to the second rotation gave no growth response (reported in Huong et al. 2008) despite the high growth rates of the stand. At the end of the second rotation, two consecutive harvests of wood and bark would have removed 84.7 kg ha^{-1} P (Table 3.1). In the third rotation, application of P improved growth significantly even with the retention of slash and litter over successive rotations (Table 3.4). Harwood et al. (2014) found a small response to P application at five years after planting of acacia hybrid (second rotation) in central Vietnam. Even when the extractable P levels were low, response of *A. mangium* in Sumatra to added P was small or transient (Hardiyanto and Wicaksono 2008), and often a small addition of 5 - 10 g P at planting seems adequate to meet the need for a rotation. It is likely that P will become more limiting over successive rotations. In order to assess this, improved methodology to measure available P based on research is required as the currently used methods do not accurately reflect capacity of the roots to acquire P from the soil (Hardiyanto and Nambiar 2014).

Soil organic carbon and N in the top soil increased from the end of first to the end of the second rotation (Figure 3.1a and b) in all treatments. Single slash and litter retention (harvesting stem wood + bark only) increased SOC by 26% and N by 40% after six years compared to pre-treatment levels (Figure 3.1). Although no information on rates of organic matter decomposition in this environment is available, field observation suggests that it is likely to be rapid, given high temperature and moisture levels, and high nutrient concentrations within the slash (Vitousek et al. 1994). The highly consistent and parallel trends in SOC and N found in our study (Figure 3.1) stands out from the results, from other acacia and eucalypt sites managed over short rotations (summarized in Nambiar and Harwood 2014). At most of these sites, SOC and N either remained unchanged or tended to show only minor increase over a rotation. For example, Harwood and Nambiar (2014) found that topsoil SOC and N in the showed no significant trend over time at a second-rotation *A. mangium* site in South Sumatra, possibly due to high variation in the data, but also the initial soil SOC (27 - 35 g kg^{-1}) and N (2.2 g kg^{-1}) concentrations were higher in that soil than in ours, which may have some influence on the accretion capacity. When soil was sampled in our study, contamination from the decomposed litter was avoided as much as practical. However, some error (leading to potential over estimation) due to contamination cannot be discounted. But the error bars in Figure 1a and 1b are small (coefficient of variation for SOC ranged from 1.5 to 9.4% and for N from 5.4 to 10%) giving confidence that the increases in SOC and N over time are reliable measures. It is likely that inputs of carbon from organic matter cycling and N (from organic matter and by fixation), fine root turnover and minimal site disturbance together have enabled SOC and N gain at this site. There are no estimates available for N-fixation by acacias in Vietnam. Bouillet et al. (2008) reported that in an acacia-eucalypt mixed species trial in Brazil *A. mangium* at age 30 months had estimated fixation rates in the range of 30 - 65 kg ha^{-1} N depending on the method of measuring N-fixation. Higher rates were reported for fast growing *A. mangium* in Sumatra (Wibisono et al. 2015).

The increase in productivity over the three rotations (Table 3.5) illustrates the potential for achieving improvements in Vietnam. The limitations in interpreting productivity changes across rotations are known (O'Hehir and Nambiar 2010), because each rotation is subject to different bio-physical and management regimes. The improvements in stand growth and soil properties reported in this study were achieved by several factors acting in a complementary way. They include: quality of management which promotes optimum initial stocking and survival (Huong et al. 2008), deployment of genetic material from seed orchard stock and then to clones, conservation of site organic matter and nutrients and application of a small dose of P.

The effects of genetic improvement can be substantial. For example, at age four years, *A. auriculiformis* plantations grown at three locations from material from seed orchard had an average MAI of 27.7 $m^3 ha^{-1} yr^{-1}$ compared to 12.1 $m^3 ha^{-1} yr^{-1}$ for commercial seed-lots (Hai et al. 2008). The additive nature the contributions of genetics, stock control, and management in increasing production have been shown in field operation with eucalypts in South Africa (Morris 2008) and Brazil (Gonçalves et al. 2013). The much higher stocking in the second rotation (Table 3.5) was another reason for the productivity increase (Dung et al. 2005). Weed control is also an important factor. Herbicide application in 1.5 m wide strips along tree rows increased the volume of acacias by 52% at age four years compared to no application of herbicide after planting (Huong et al. 2008). The impacts of conserving site resources have been over and above this, and such practices are essential for sustaining production over multiple rotations in a range of systems (O'Hehir and Nambiar 2008, Laclau et al. 2010, Gonçalves et al. 2013, Nambiar and Harwood 2014). The best treatment in the third rotation (Table 3.4) achieved an MAI of 37 m^3 ha^{-1} yr^{-1}, which is the highest productivity measured so far in any experimental plantation in Vietnam.

3.5. Conclusion

We found significant increases in productivity over three rotations in an *A. auriculiformis* plantation in Vietnam. It is likely that improved stocking rates, site management and planting of genetically improved stock contributed to these improvements. Removal of slash and litter after harvesting a low yielding first rotation crop reduced the standing volume of the next faster growing rotation by 13% compared to treatments with slash and litter retained. Slash and litter retention also reduced the soil bulk density and increased soil organic carbon content by 26% and nitrogen by 40% in the 0 - 10 cm soil compared to levels at the start of the second rotation. Soil organic matter and nitrogen also increased with stand age irrespective of treatment, but there were no trends in soil pH over time. Extractable soil P declined during the second rotation, but there was no growth response to P fertilizer at that time. However, there was a response to added P in the third rotation. In southern Vietnam, substantial increases in productivity of *A. auriculiformis* plantations can be achieved over several rotations through improved and integrated management practices.

Chapter 4. Growth and physiological response of *Acacia auriculiformis* plantations to mid-rotation thinning, application of phosphorus fertiliser and organic matter retention in South Vietnam

Vu Dinh Huong [1,2,3*], Daniel S. Mendham [2] and Dugald C. Close [3]

[1] Forest Science Institute of South Vietnam, Ho Chi Minh City, Vietnam.

[2] CSIRO Land and Water, Private Bag 12, Hobart, Tasmania 7001, Australia.

[3] Tasmanian Institute of Agriculture, School of Land and Food, University of Tasmania, Private Bag 98, Hobart, Tasmania 7001, Australia.

*Corresponding author, e-mail: Huong.VuDinh@utas.edu.au

Abstract

Acacia auriculiformis plantations are widely planted in Vietnam. Initially they were harvested for wood chip production, but these plantations have potential to be managed for higher value sawing and/or peeling grade logs, through enhanced silvicultural management. This study sought to understand the impacts of resource constraints on responses of *A. auriculiformis* plantations to thinning, phosphorus fertiliser application and slash retention at age four years on the growth and physiology of *A. auriculiformis* trees to rotation end at age seven years. The experiment, established in South Vietnam, was laid out in a randomised complete block design with six treatments and three replicates. Treatments included: un-thinned, no P and litter removed (T0P0S0); un-thinned, 50 kg P ha^{-1} and litter retained (T0P1S1); thinned to 833 trees ha^{-1}, no P and litter and slash retained (T1P0S1);

thinned to 833 trees ha^{-1}, no P and litter and slash removed (T1P0S0); thinned to 833 trees ha^{-1}, 50 kg P ha^{-1} and litter and slash retained (T1P1S1). Thinning significantly increased photosynthetic rate (A_{max}) compared to control (unthinned) for at least 12 months after treatment application.

Combined thinning and phosphorus fertiliser (P) application increased A_{max}, but A_{max} in the unthinned treatment did not significantly increase when supplied with additional P. Foliar nitrogen and phosphorus concentration were greater in thinned than in unthinned treatments. Leaf area increased in the thinned treatment relative to the unthinned treatment, such that 20 months after thinning there were no significant differences in leaf area index between thinned plus P fertiliser and unthinned treatments. There were significant differences in the mean diameter of trees under different thinning regimes after one year. These differences were sustained for three years after thinning. The application of P fertiliser or differences in management of slash and litter had no significant effect on mean tree diameter. The recovery of larger sawn timber in thinned treatments was significantly higher than in unthinned treatments. At seven years, the total stand value of wood products in the thinned treatments (including the thinning harvested in year 4) was higher (US$ 900) than for the unthinned treatments. The results suggest that a commercial mid-rotation thinning of *A. auriculiformis* in these environments can increase the value of these plantations to acacia growers.

Key words: Acacias, phosphorus, leaf area index and litterfall.

4.1. Introduction

Timber processing industries are an important part of the Vietnamese economy, with exports of over US$ 6.5 billion in 2014. Despite this approximately 65% of raw timber materials are imported into Vietnam (AGROINFOR 2014). *Acacia auriculiformis* was introduced into Vietnam in the 1960s and these plantations have proven to be suitable for planting in lowland environments throughout the country for both timber and pulp production (Nghia 2003a). Currently, there are approximately 90,000 ha of *A. auriculiformis* plantations in Vietnam (Phat 2011, Nambiar and Harwood 2014).

To date most acacia plantations in Vietnam have been established and managed over short rotations of 5 – 8 years for pulpwood production, and therefore have not yielded a high proportion of saw-logs. However, there may be significant economic advantages for typical small-holder farmers to target sawlog production instead of, or as well as, pulpwood production (Blyth and Hoang 2013). The Vietnamese government is looking to support the conversion of existing areas of *A. auriculiformis* plantations from management for pulpwood to management for solid wood production (MARD 2014), by adopting practices such as thinning and slash and litter retention.

If a commercial thinning operation is practiced, as part of a sawlog rotation, it is common for branches and leaves (slash) to be collected by local people for fuel, but such practices in clear-fallen pulpwood stands have been shown to deplete the nutrient reserves and degrade the site productive capacity. For example, the removal of 20.2 Mg ha^{-1} of slash and litter at age six years from an *A. auriculiformis* plantation with an initial density of 833 tree ha^{-1}

resulted in the loss of 169.6 kg ha^{-1} N, 14.9 kg ha^{-1} P and 76.3 kg ha^{-1} K (Huong et al. 2015). A review of results from tropical and subtropical experiments, using a range of fast-growing plantation species, concluded that there was a 10 - 60% decline in production induced by poor inter-rotation management practices, including the removal of slash and litter between rotations (Nambiar and Harwood 2014).

Intensive silvicultural practices, including thinning, pruning and fertiliser application, can increase plantation growth rates, increase the proportion of saw-logs, and maximise the value of plantation forests (Medhurst et al. 2001, Forrester et al. 2012a). Understanding how these management interventions affect light availability, photosynthesis, canopy leaf area and tree growth rate is important in order to optimize the decision-making around timing and intensity of different management options.

Thinning is applied to increase the availability of resources (light, nutrients and water) to the retained trees (Breda et al. 1995, Medhurst and Beadle 2001, Medhurst and Beadle 2005, Davi et al. 2008, Forrester et al. 2012b), thus resulting in larger, more valuable logs. The magnitude of the response to thinning depends on the capacity of the trees to utilize the additional resources available to them. For instance, significant increases in photosynthesis in lower and middle crown zones was found after thinning *Eucalyptus nitens* at age 8-year-old (Medhurst and Beadle 2005). Forrester et al. (2012b) showed that the photosynthetic rate of *Eucalyptus nitens* at age 3.2 yr increased by 9.5%, 19 weeks after thinning, suggesting that growth in these stands was limited by light.

Phosphorus (P) is one of the principal nutrients found to be limiting tree growth and productivity in tropical forests (Vitousek 1982, Attiwill and Adams 1993), and it is also important for enhancing the nitrogen (N) fixing capacity of legume species (Adams et al. 2010). Therefore, nutrient management has been widely researched with a focus on maintaining sustainable production and improving wood quality in plantation forests (Webb et al. 2000, Smethurst et al. 2003, Wiseman et al. 2009, Mendham et al. 2010, White et al. 2010, Forrester et al. 2012a). Mendham et al. (2010) found that *A. mangium* plantations responded strongly to P fertiliser at establishment, but that the level of the response declined over time after establishment at a range of sites in South Sumatra. However, the level of the response declined over time: only 10 kg ha^{-1} P was required to achieve maximum productivity levels by age 3 yr at all sites (Mendham et al. 2010). While previous studies in acacias have shown a response at establishment, the presence and/or magnitude of response to P fertiliser at thinning in tropical acacias has not been reported previously.

The impact of thinning on the physiological responses of temperate eucalypt and pine plantations has been widely reported in the literature (Tang et al. 2003, Mäkinen and Isomäki 2004, Medhurst and Beadle 2005, Forrester et al. 2012b, Forrester et al. 2013). Despite this depth of knowledge, there have been no reported studies on the physiological responses of tropical *A. auriculiformis* plantations to thinning, slash retention and fertiliser application. Therefore, the objectives of this study were to: (1) quantify biomass and nutrients in thinning slash and litter and rates of decomposition under contrasting thinning practices, (2) test the hypothesis that *Acacia auriculiformis* trees will respond positively to phosphorus fertiliser (P), slash and litter retention (slash) and thinning at age four years as measured by changes in photosynthetic rates (A_{max}), leaf area index (LAI) and litterfall, and (3) test the hypothesis that the addition of P, slash retention and thinning increase the production and volume of larger diameter logs in *A. auriculiformis* plantations.

4.2. Methodology

4.2.1. Location, climate and soil

The site was located in South Vietnam at Phu Binh (11.3° N, 106.8° E). The region has a mean annual maximum temperature of 35.6°C, mean annual min temperature of 21°C and annual rainfall of 2 800 mm yr^{-1} with a marked dry season, typically from December to March. The soil type is a Chromic Acrisol, with a sandy clay loam A horizon, grading to a sandy clay B horizon. Key soil properties in the 0-20 cm horizon were: bulk density 1.33 (± 0.01) g cm^{-3}, clay 26.52 (± 0.29) %, pH (H_2O) 4.58 (± 0.02), pH (KCl) 3.88 (± 0.01), soil organic carbon (SOC) 14.1 (± 0.1) g kg^{-1}, total nitrogen (N) 1.21 (± 0.01) g kg^{-1} and extractable phosphorus (P) 10.42 (± 1.47) mg kg^{-1}.

4.2.2. Experimental establishment

The stand was planted to *Acacia auriculiformis* with a random mixture of clones AA1 and AA9 (Nghia et al. 2010) in July 2008 at a spacing of 3 m × 2 m (equivalent to 1666 trees ha^{-1}). Any clone effect or interaction was avoided through the random mixing of clones prior to planting. At planting, 50 g of 16-16-8 NPK fertiliser was applied per tree, equivalent to 13.3 kg P ha^{-1}, 13.3 kg N ha^{-1} and 6.7 kg K ha^{-1}. Weeds were controlled by spraying glyphosate (1.92 kg ha^{-1}) just prior to planting and annually after planting.

4.2.3. Experimental design

The experimental treatments were implemented in July 2012 when the stand was four years old. The experiment was laid out in a randomised complete block design with six treatments and three replicates. The treatments were:

T0P0S1: un-thinned (initial stocking, 1666 trees ha^{-1}), no phosphorus fertiliser (P) and litter retained;

T0P0S0: un-thinned, no P and litter removed;

T0P1S1: un-thinned, 50 kg P ha^{-1} and litter retained;

T1P0S1: thinned to 833 trees ha^{-1}, no P and litter and slash retained;

T1P0S0: thinned to 833 trees ha^{-1}, no P and litter and slash removed;

T1P1S1: thinned to 833 trees ha^{-1}, 50 kg P ha^{-1} and litter and slash retained.

Gross treated plot size was 21 × 24 m (7 × 12 trees), with 1 buffer row, resulting in a net (measured) plot size of 15 × 20 m (5 × 10 trees). The rate of 50 kg P fertilizer per ha was chosen to represent a non-limiting rate (Mendham et al. 2010, FSIV, unpublished data).

4.2.4. Measurements

4.2.4.1. Sampling for estimates of litter, understorey vegetation and slash

Before thinning, four 1 m^2 sample plots were randomly located in each of the T0P0S0 and T1P0S0 treatment plots for litter and understorey biomass sampling. Litter was separated into leaf, wood, bark, branches, flowers, seeds, pods, and stalks. The understorey vegetation was divided into woody and non-woody plants; each category was separated further into leaf, wood, bark and branches. Litter and understorey vegetation components were oven dried to constant weight at 65°C.

Slash (leaf and branch) biomass retained at the site after thinning was estimated by using equations 1 and 2 (below), derived from 10 trees with diameters between 8 and 13 cm that were destructively sampled at age four years:

(4.1) $\ln(\textit{leaf weight, kg}) = 2.8075 \ln(\textit{DBH, cm}) - 5.945$ ($R^2 = 0.96$, n = 10)

(4.2) $\ln(\textit{branch weight, kg}) = 3.4038 \ln(\textit{DBH, cm}) - 7.4629$ ($R^2 = 0.91$, n = 10)

Subsamples of each of the litter, understorey vegetation, and slash components were analysed for N, P and K.

4.2.4.2. Slash decomposition

Slash components including leaf (L), branches with diameter less than one cm (Br<1cm) and branches with diameter between one and five cm (Br1-5cm) were sampled by harvesting 10 trees at age four years from thinned plots (T1P0S1, T1P0S0 and T1P1S1). Slash components were oven dried at 65°C to constant weight. Nylon bags (25 x 25 cm, mesh size 2mm) containing 15 g (dry weight) of L, Br<1cm and Br1-5cm (84 bags of each) were spread randomly over the soil surface of three T0P0S1 plots and three T1P0S1 plots. Each plot received 42 bags including 14 bags of L, 14 bags of Br<1cm and 14 bags of Br1-5cm. The study was conducted from 15 October 2012 to 15 November 2014 with monthly collection intervals from November 2012 to May 2013 and then with three monthly collection intervals between June 2013 and November 2014. At collection, three bags of each slash component were randomly chosen in each plot and oven dried at 65°C to constant weight. Samples were weighed and the percentage of slash mass lost during the study time was calculated.

4.2.4.3. Photosynthetic light response measurements

Response of the foliar photosynthesis to light level was assessed between 09:00 and 14:00 h under clear to partly cloudy skies at first at seven weeks and then one year after the thinning application. At seven weeks, four trees were randomly selected in each of the T0P0S1, T0P1S1, T1P0S1 and T1P1S1 treatments. At one year after thinning, three trees were randomly selected in each of the T0P0S1, T0P1S1, T1P0S1 and T1P1S1 treatments. One branch, 10 - 20 mm diameter, was selected from middle crown zone of each of the selected trees. These branches were excised at the base from the sunlit side of the tree and placed immediately in a bucket of water, and then re-cut under water to avoid embolism (Turnbull et al. 2007, Eyles et al. 2011). One fully-expanded leaf from each branch was selected for measurements. Sixteen and 12 leaves, respectively, were measured at seven weeks and one year after thinning, giving a grand total of 28 leaves.

Light response curves were measured with a LICOR-6400 portable photosynthesis system (Li-Cor Inc., Lincoln, NE, USA) with a standard 20 x 30 mm chamber equipped with blue-red emitting diodes mounted on the top of the chamber (Model 6400-02B). Measurements were made at light levels of 2000, 1500, 1000, 650, 300, 200, 100, 50 and 0 μmol m^{-2} s^{-1}.

The leaf chamber environment was maintained at 400 μmol CO_2 m^{-2} s^{-1}, and at 25°C. Light-response curve parameters of apparent quantum yield (Φ), light-saturated photosynthesis (A_{max}) and dark respiration (R_{dark}) were estimated from the fitted non-rectangular hyperbolic functions of net CO_2 uptake versus PAR (Sands 1995).

Following completion of light response measurements, leaf samples were excised and placed into zip-lock plastic bags, stored on ice and then refrigerated until being assessed for specific leaf area (SLA, cm^2 g^{-1}), and dried for leaf N and P analysis (see below). For leaf area, leaves were scanned and images analysed for leaf area using Image J v1.37 (Abramoff et al. 2004). Leaf N and P concentrations (mg g^{-1}) and contents (mg cm^{-2}) were calculated on an air-dry mass and area basis.

4.2.4.4. Leaf area index (LAI)

Leaf area index (LAI) was assessed in all treatments by calibrated digital photography (Nikon Coolpix L29 Digital Camera, Nikon Camera, Japan) at three-monthly intervals after the first thinning application in July 2012. Photographs were taken from 10 fixed positions (marked by stakes), placed in two parallel lines diagonally through the middle of each plot. This arrangement was designed to capture any heterogeneity in the distribution of the canopy in space, particularly in the thinned plots. To estimate LAI, the digital photographs were analysed using Fiji-win32 image analysis software, with an automated thresholding algorithm to convert to black and white, and extraction of the gap fraction as the proportion of white in the image. The gap fraction converted to an estimate of LAI using Beers law of light extinction. These digital camera estimates of LAI were calibrated against measures of plant area index (PAI) made in April and July 2014 at the same points using a Li-Cor LAI-2000 Plant Canopy Analyser

$$(PAI = 0.06922LAI_{camera} + 0.176 \qquad [R^2 = 0.98; n = 36; P < 0.001]) \qquad (4.3)$$

and PAI converted to actual LAI using an equation developed by Battaglia et al. (1998):

$$LAI = 1.54PAI - 0.11 \quad (R^2 = 0.99) \qquad (4.4)$$

4.2.4.5. Litterfall sampling

To compare the effects of P fertilizer and thinning time on litterfall, two 1 m^2 area litter traps were placed at random locations within each plot of the T0P0S1, T0P1S1 and T1P1S1 treatments after thinning in July 2012. Litter was collected at monthly intervals from September 2012 to July 2015. Each collection was taken to the laboratory, dried at 65ºC for 48 h and weighed for dried mass calculation.

4.2.4.6. Tree growth

Tree diameter over bark at breast height (DBH at 1.3 m) was measured just before thinning and then approximately every six months during the experiment. Tree height was estimated by using Equation 4.5, which was derived from 60 tree samples from standing age four to age seven years with diameters between 8 and 20 cm:

$$Y = 13.926 \ln X - 15.84 \ (R^2 = 0.86, n = 60) \qquad (4.5)$$

where Y is tree height (in m) and X is DBH (in cm).

Standing volume of each tree was calculated by using an equation (4.6) below (Huong et al.

2015):

$$V = \pi \left(\frac{D}{200}\right)^2 * H * F \quad (4.6)$$

where V is standing volume (in m^3), D is DBH (in cm), H is total height (in m) and F is a form factor (F = 0.475).

At age seven years, the distribution of log sizes from a potential harvest were derived through destructive sampling of 15 trees with DBH in the range 10 cm to 20 cm. Allometric relationships were developed to predict volumes of pulpwood (V_{PW}), small sawlog (V_{SSL}) and large sawlog (V_{LSL}) from each individual tree (Equations 4.6 and 4.7).

Volume of pulpwood (V_{PW}) for each individual tree was calculated according to the following rules:

- if tree DBH <10 cm, V_{PW} = 100% of total tree volume (V);
- if 10 cm ≤ tree DBH <20 cm, the formula was used as:

$$\ln (V_{PW}) = -2.8687 \ln (DBH) + 10.933 \quad (R^2 = 0.93, n = 15) \quad (4.7)$$ where DBH in cm;

- if tree DBH ≥20 cm, V_{PW} = 7 % of V.

Volume of large saw-log (V_{LSL}) as a percentage of total volume for each individual tree was calculated according to the following rules:

- if tree DBH <15 cm, V_{LSL} = 0% of V

- if 15 cm ≤ tree DBH ≤ 20 cm the formula was used as:

V_{LSL} = 10.684*DBH - 135.95 (R^2 = 0.99, n = 9) (4.8) where DBH in cm;

- if tree DBH >20 cm, V_{LSL} = 88 % of V

After calculating the volumes of pulpwood and large saw-log in each tree using these relationships, the volume of small saw-log (10-14 cm diameter, V_{SSL}) for each tree was calculated by subtraction: $V_{SSL} = V – V_{LSL} –V_{PW}$ (4.9)

For a simple economic analysis of the value of the standing and/or thinned timber in each of the treatments (not accounting for input costs, or the cost of money), the prices of pulpwood, small saw-log and large saw-log were based on average prices paid at the mill gate in 2015 in South Vietnam. These were US$ 50 m^{-3} for pulpwood, US$ 65 m^{-3} for small saw-log and US$ 100 m^{-3} for large sawlog.

4.2.4.7. Nutrient analysis

Dried samples of litter, understorey, slash and leaf samples (from the gas-exchange measurements) were weighed and ground in a hammer mill to ≤ 0.02 mm. Subsamples (~0.5 g) were digested in concentrated sulphuric acid and 30% hydrogen peroxide. Nutrient concentrations were measured in the digest according to methods of Rayment and Higginson (1992), as adapted by the Forest Science Institute of South Vietnam: N- Kjeldahl method, potassium (K) and phosphorus (P) determined by an ANA-720W spectrophotometer (Tokyo Photo-electric Company Limited, Japan).

4.2.5. Statistical analysis

Analysis of variance (ANOVA) and repeated measures ANOVA were used to test for treatment effects on tree growth and ANOVA was used to test for differences in tree physiological attributes between treatments. A *P* value of < 0.05 was taken to indicate a significant difference between means. Where a significant difference was detected, comparisons were made using the least significant difference (LSD) in a multiple range test. Statistical analysis was conducted using Genstat (13th Edition, VSN International 2011).

4.3. Results

4.3.1. Effects of thinning on organic matter, nutrients and decomposition rates at the site

The average quantity of biomass in the thinned treatments was 5.8 Mg ha^{-1}, comprising 71.2, 6.3 and 24.4 kg ha^{-1}, of N, P and K respectively and the ratio of N:P:K was 11.4:1:3.9 (Table 4.1). Litter accumulated on the forest floor and ratios of constituent N:P:K were not significantly different between treatments before thinning. There were no significant differences in the quantity of slash retained after thinning in the thinned treatments (T1P0S1 and T1P1S1).

Table 4.1 Organic matter and nutrient content of slash, litter and understorey after thinning treatments at stand age of four years.

Components	Dry mass (Mg ha^{-1})	Nutrient contents (kg ha^{-1})			Ratio
		N	P	K	N:P:K
Slash					
Branches	4.5	39.2	4.0	14.3	
Leaves	1.3	32.0	2.3	10.1	
Total	5.8	71.2	6.3	24.4	11.4 : 1 : 3.9
Litter & Understorey					
Litter	1.9	22.7	0.6	8.5	
Understorey	0.3	2.6	0.1	1.2	
Total	2.2	25.4	0.6	9.7	39.9 : 1 : 15.3

The decomposition rate of leaf material was significantly higher than that of branch material (Figure 4.1). Two months experiment was initiated, leaf mass had decreased by around 75 % while mass loss of branches was between 12 and 17 %. Seven months later, leaf material had fully decomposed, but the remaining mass of branches with diameter less than 1cm (Br<1cm) and between 1 and 5 cm (Br1-5cm) were about 60 % and 70 % respectively. Most of the Br<1cm material had fully decomposed by 21 months, while the Br1-5cm fraction was slightly slower to decompose, reaching 95 % mass loss by 24 months. Thinning treatment did not affect the rates of decomposition between treatments, but there was a trend for slash components in the thinned treatment (T1P0S1) to decompose more rapidly than in the unthinned treatment across all of the litter fractions (T0P0S1) (Figure 4.1).

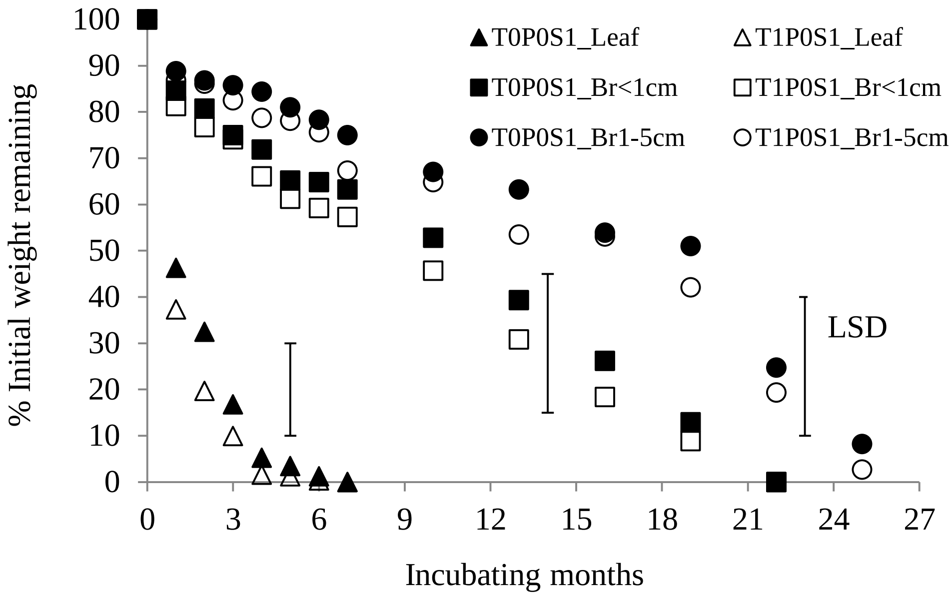

Figure 4.1 Mass loss in decomposing slash during two years of study. Vertical bars indicate least significant difference (LSD) at $P < 0.05$ for treatments.

4.3.2. Photosynthetic rate

There were significant differences (P < 0.01) between thinning treatments in the light response curves of photosynthesis at both seven weeks (in 2012) and one year (in 2013) after thinning (Figure 4.2a). However, there were no significant effects of the slash treatment on light response curves. Maximum light saturated photosynthesis rates (A_{max}) decreased significantly from 2012 to 2013 irrespective of treatment (Figure 2b). The thinned treatments had significantly greater A_{max} (P < 0.01) than the unthinned treatments. Trees that received an application P fertiliser also had a higher A_{max} than unfertilized (nearly significant, P =0.056). However, there was no significant response of A_{max} to P fertiliser in the unthinned treatments (Figure 4.2b). There were no significant effects of treatment on stomatal conductance or dark respiration at either measurement time.

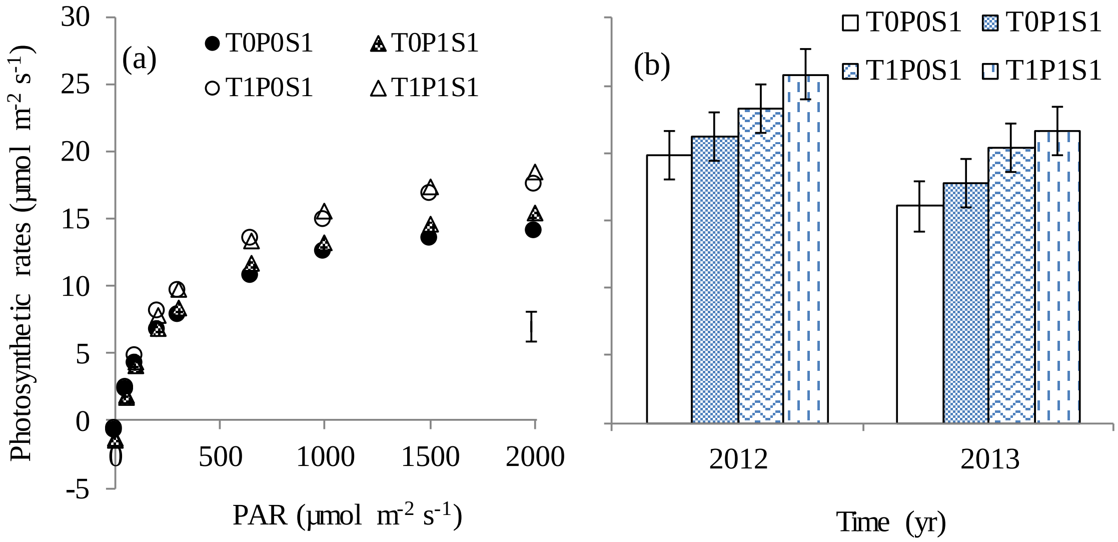

Figure 4.2 (a) Photosynthesis light response curves of *A. auriculiformis* trees (n = 28) between 2012 and 2013; (b) Effects of time, thinning and fertiliser application on photosynthesis rate (A_{max}) of *A. auriculiformis* trees (n = 28). Errors bars indicate: (a) least significant difference between treatments (LSD) and (b) standard error of difference of mean between treatments (SED).

4.3.3. Leaf area index

Leaf area index (LAI) of all treatments tended to increase through the wet season from May to October, climbed to a peak in December, and then declined during the dry season from November to April (Figure 4.3). Immediately after thinning in August 2012 at age four years, LAI of thinned treatments was significantly lower than that of unthinned treatments. LAI remained lower in thinned treatments compared to the unthinned treatments ($P < 0.05$) at all measure times. However, LAI of thinned and P fertilised treatment (T1P1S1) was not significantly different compared to unthinned without P fertiliser treatments (T0P0S1 and

T0P0S0) from April 2014 to July 2015 (Figure 4.3).

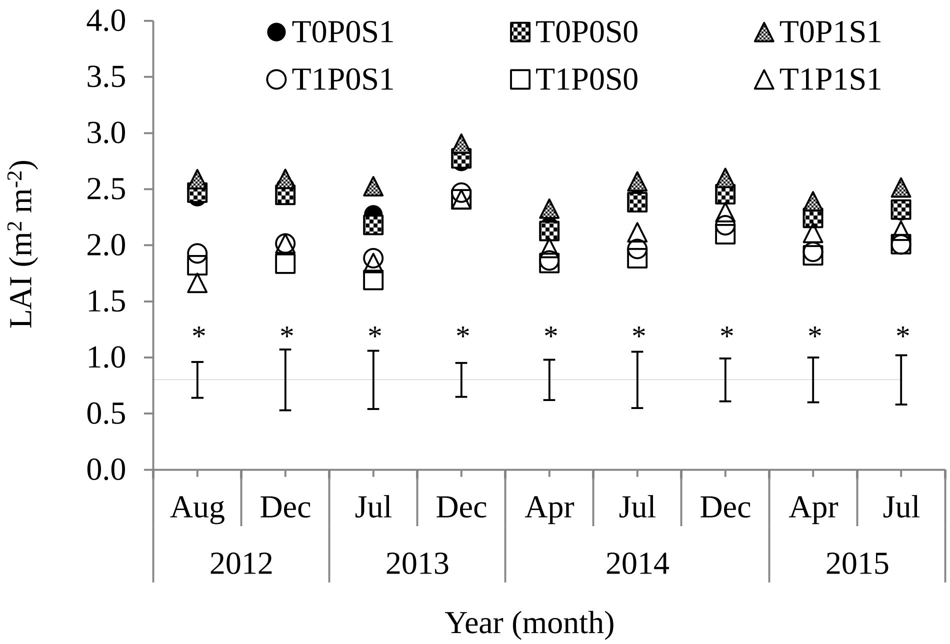

Figure 4.3 Effects of thinning treatments on leaf area index (LAI) of *A. auriculiformis* plantations from age 4 to age 7 yr. Vertical bars indicate least significant difference (LSD) at $P < 0.05$ for LAI. Asterisks indicate significance of treatments *(P* < 0.05*):**.

4.3.4. Litterfall

Most of the total litterfall occurred during the dry months with the highest litterfall in November, December, and January (Figure 4.4). In September 2012, two months after thinning, there was no influence of thinning on litterfall, but on most occasions between October 2012 and May 2013, litterfall in the thinned treatment (T1P1S1) was significantly lower than in the unthinned treatments (T0P0S1 and T0P1S1). During the period between May 2013 and July 2015, there were no significant differences in litterfall between treatments except in the driest months (January, February 2014 and February 2015), where the thinned treatment tended to have lower litterfall. In the unthinned treatment, P fertilizer had no influence on litterfall up to 3 yr after treatment application (Figure 4.4).

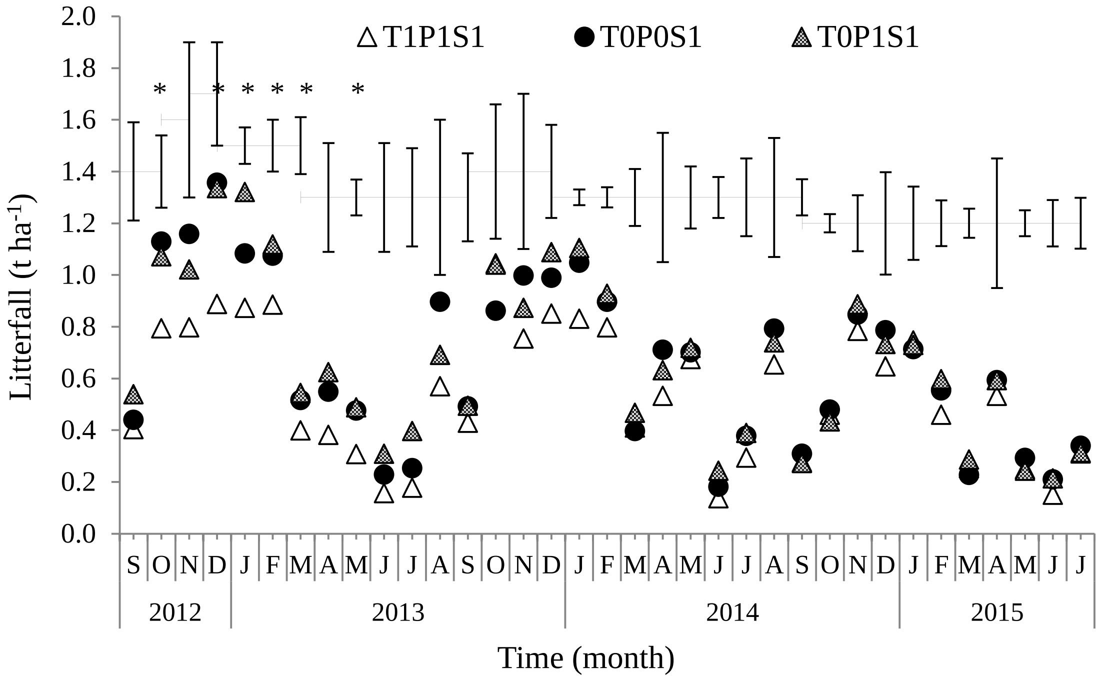

Figure 4.4 Effects of thinning treatments on litterfall production of *A. auriculiformis* plantations from age 4 to 7 yr. Vertical bars indicate least significant difference (LSD) at $P <$ 0.05 for monthly litterfall. Asterisks indicate significance of treatments *(P* < 0.05*):**.

4.3.5. Specific leaf area, foliar nitrogen and phosphorus content

Specific leaf area (SLA) ranged from 66.7 ± 4.4 to 106.9 ± 10.4 $cm^2\ g^{-1}$. SLA was not significantly affected by thinning or P fertiliser application at either seven weeks or one year after thinning (results not shown), although the average SLA of thinned treatments (T1P0S1 and T1P1S1), 75.0 ± 3.9 $cm^2\ g^{-1}$, tended to be lower than unthinned treatments (T0P0S1 and T0P1S1), 89.1 ± 3.9 $cm^2\ g^{-1}$. In contrast, at seven weeks after thinning, foliar nitrogen (N) concentration expressed on a mass basis (mg g^{-1}) was significantly lower (P = 0.007) in unthinned (21.1 ± 0.6 mg g^{-1}) than thinned treatments (23.2 ± 0.6 mg g^{-1}); but this difference was not found one year later (Table 4.2). There was no significant difference in foliar N content expressed on an area basis (mg cm^{-2}) between treatments seven weeks or one year after thinning. There were significant differences where foliar phosphorus (P) where the concentration of T1P1S1 was higher than in the unthinned treatments (T0P0S1 and T0P1S1), but foliar P of T1P0S1 was only higher than that of T0P0S1 (Table 4.2).

Table 4.2 Distribution of foliar phosphorus concentration (mg g^{-1}) by leaf age for thinned and unthinned treatments. Different letters indicate means are significantly different at P < 0.05.

Time after thinning	Treatments	Nutrient concentration (mg g^{-1})	
		Nitrogen	Phosphorus
Seven weeks	T0P0S1	21.1 ± 0.7^{b}	1.6 ± 0.1^{c}
	T0P1S1	21.0 ± 0.4^{b}	1.7 ± 0.1^{bc}
	T1P0S1	22.5 ± 1.2^{a}	2.1 ± 0.1^{ab}
	T1P1S1	23.8 ± 0.7^{a}	2.4 ± 0.1^{a}
One year	T0P0S1	24.7 ± 0.5^{a}	1.3 ± 0.1^{c}
	T0P1S1	25.6 ± 0.7^{a}	1.4 ± 0.1^{bc}
	T1P0S1	25.9 ± 0.6^{a}	1.6 ± 0.1^{ab}
	T1P1S1	26.1 ± 0.4^{a}	1.7 ± 0.1^{a}

4.3.6. Tree growth

Before thinning at age four years, tree survival was around 80% for all plots allocated to the different treatments. Immediately after thinning, the mean survival rate of residual stems in the thinned treatments was 97.3 ± 1.3 % and this remained constant over the subsequent three years.

Immediately after thinning, there were no significant differences between treatments in tree diameters (DBH, Table 4.3). Three years later at age seven years mean DBH of thinned treatments (T1P0S1, T1P0S0 and T1P1S1; 16.73 ± 0.13 cm) was significantly greater than that of unthinned treatments (T0P0S1, T0P0S0 and T0P1S1; 14.76 ± 0.18 cm) (Table 4.3), but there were no significant effects of P fertilizer or slash management on DBH. Associated with this result were distinct groupings in the current annual increment of thinned and unthinned treatments at age 5 and 6 yr (Table 4.3). Similarly, there were no significant differences in tree height between treatments directly after thinning, but three years after thinning, the trees in the thinned treatments were significantly taller (23.3 ± 0.2 m) than those of the unthinned treatments (21.4 ± 0.2 m).

Diameter size in thinned treatments was significantly higher than in unthinned treatments three years after thinning (Figure 4.5). The percentage of tree number per ha in diameter class (16 - 18 cm) accounted for 43 % of the trees in the thinned treatments which was significant higher than that in unthinned treatments (30%). In particular, the percentage in the diameter class (>18 cm) in thinned treatments was 24% higher four times than that in unthinned treatments. There was no tree size under 10 cm in the thinned treatments (Figure 4.5).

Table 4.3 Effects of thinning, fertiliser and slash retention on diameter growth. Different letters indicate means are significantly different at $P < 0.05$.

Treatments	Stocking (trees ha^{-1})	DBH* (cm)		Current annual diameter increment (cm)			
		Age 4 yr	Age 7 yr	Age 5 yr	Age 6 yr	Age 7 yr	Total
T0P0S1	1666	11.55	14.50^{b}	1.23^{b}	1.06^{c}	0.66^{b}	2.95^{c}
T0P0S0	1666	11.76	14.73^{b}	1.17^{b}	1.09^{c}	0.71^{b}	2.97^{c}
T0P1S1	1666	12.15	15.06^{b}	1.16^{b}	1.07^{c}	0.69^{b}	2.91^{c}
T1P0S1	833	12.29	16.81^{a}	1.93^{a}	1.59^{ab}	1.00^{ab}	4.52^{ab}
T1P0S0	833	12.47	16.62^{a}	1.70^{a}	1.51^{b}	0.94^{b}	4.15^{b}
T1P1S1	833	12.05	16.79^{a}	1.88^{a}	1.78^{a}	1.08^{a}	4.74^{a}
P-value *(α = 0.05)*		0.09	<0.001	0.002	<0.001	<0.001	<0.001
LSD (P = 0.05)		0.66	0.80	0.39	0.19	0.13	0.48

*: Diameter measured immediately after thinning at stand age of four years.

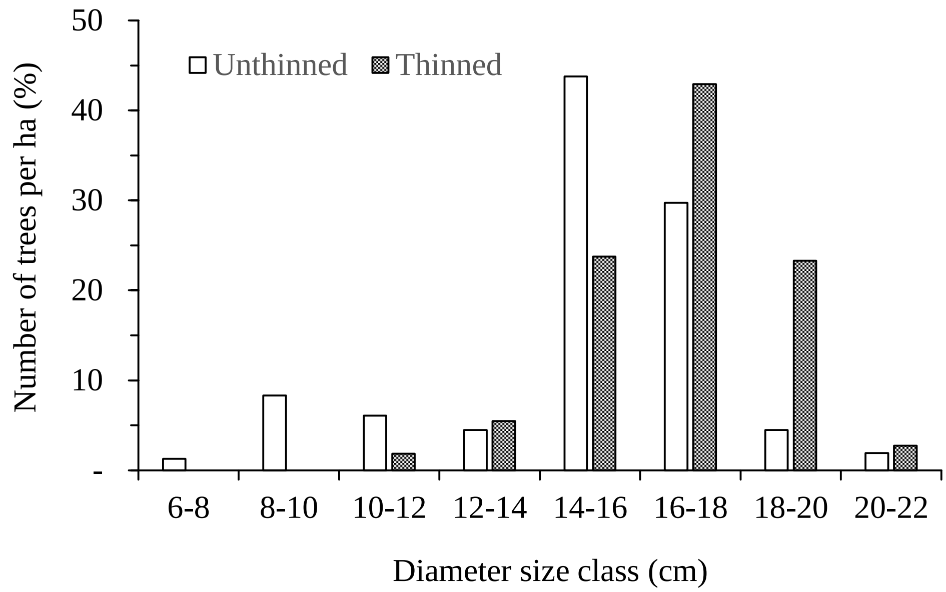

Figure 4.5 The percentage number of trees per ha in each diameter (DBH) class three years after thinning for across unthinned and thinned treatments.

The standing volume of the thinned treatments was 35% less than the unthinned treatments directly after thinning at age four years (Figure 4.6). The thinned treatments maintained a lower standing volume until the measurements ended at age six years, although the magnitude of the difference was reduced, such that there were no significant differences between treatments in total stand volume at age seven years (Figure 4.6). However, the recovery of larger logs in thinned treatments was significantly higher than that of unthinned treatments except in the T0P1S1 treatment (Table 4.4). The percentage of large sawlog product in T1P0S1 was 42.8 % of total stand volume while T0P0S1 had only 26.8 % (Table 4.4).

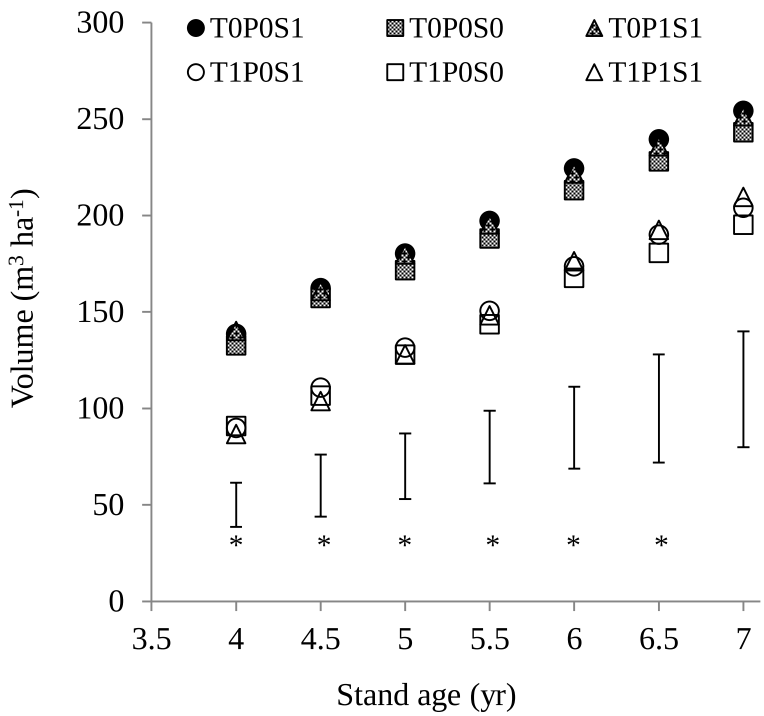

Figure 4.6 Effects of thinning, slash and phosphorus fertiliser treatments on stand volume development of *A. auriculiformis* plantations. Vertical bars indicate least significant difference (LSD) at $P < 0.05$ for stand volume. Asterisks (*) indicate significance of treatments at $P < 0.05$.

Table 4.4 Potential product recovery (m^3 ha^{-1}) at age seven years, three years after thinning, slash and phosphorus fertiliser application. Different letters indicate means are significantly different at $P < 0.05$.

Time of harvesting			4 yr	7 yr	4 yr	7 yr	4 yr	7 yr
Treatments	Stocking (trees ha^{-1})	Total volume (m^3 ha^{-1})	Pulpwood volume (m^3 ha^{-1})		Small saw-log (m^3 ha^{-1})		Large saw-log (m^3 ha^{-1})	
T0P0S1	1666	254.3	0	61.2^{a}	0	122.1^{ab}	0	71^{ab}
T0P0S0	1666	243.1	0	58.9^{ab}	0	132.7^{a}	0	51.5^{b}
T0P1S1	1666	251.4	0	55.1^{b}	0	110.9^{b}	0	85.4^{ab}
T1P0S1	833	257.3*	24.1	34.6^{c}	26.5	81.5^{c}	2.85	87.7^{a}
T1P0S0	833	245.2*	20.76	33.7^{c}	25.8	76.3^{c}	3.52	85.1^{ab}
T1P1S1	833	252.2*	20.38	35.6^{c}	22.1	83.0^{c}	0	91.1^{a}

*: Volume calculated including volume harvested from thinning at stand age of four years.

Due to the higher value of larger logs, the total standing value of wood products at year seven in the thinned treatments (including the trees harvested in year four) was higher than for the unthinned treatments at the full rotation of seven years (Figure 4.7).

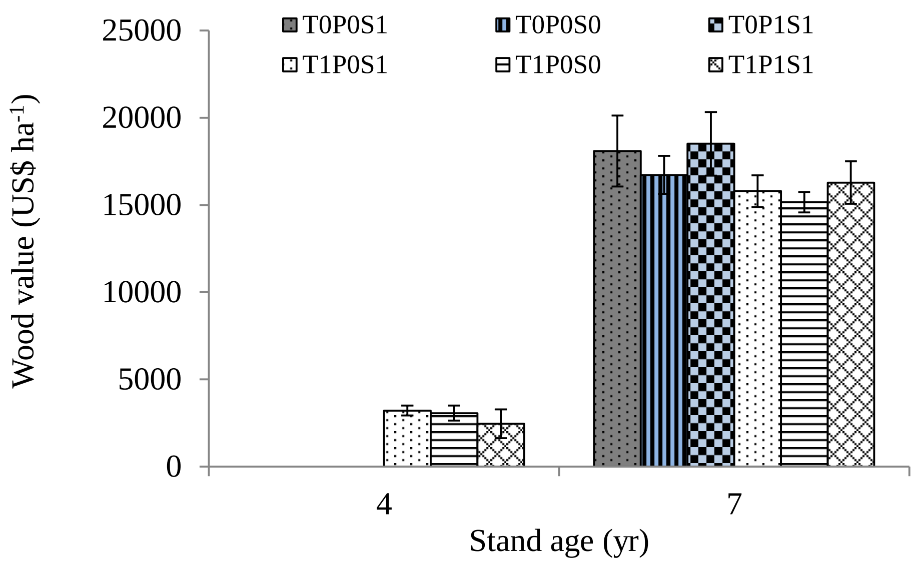

Figure 4.7 Estimated value (US\$ ha^{-1}) of wood products (m^{3} ha^{-1}) at sawlog mill gate from six treatments at stand age of four and seven years after thinning. Bars indicate standard errors (SE).

4.4. Discussion

Our finding that foliar photosynthetic rate increased after thinning is supported by studies in temperate environments that have shown that thinning can significantly increase light availability (Wang et al. 1995, Tang et al. 2003, Medhurst and Beadle 2005, Gauthier and Jacobs 2009, Forrester et al. 2012b), and photosynthetic activity. For example, Wang et al. (1995) found that thinning of four paper birch stands (9-13 years-old) from initial densities between 11000 and 31000 trees ha^{-1} down to 400, 1000 and 3000 trees ha^{-1} resulted in an increased A_{max} with increased thinning intensity. Gauthier and Jacobs (2009) also showed that light level incident on leaves of unthinned trees (775 µmol m^{-2} s^{-1}) was significantly lower than that in thinned trees (1475 µmol m^{-2} s^{-1}) one year after thinning of *Juglans nigra* plantations, with a corresponding strong positive relationship with photosynthetic rate. Thus the increased A_{max} observed in this study is likely due to increased incident light on the remaining trees as a result of thinning.

Thinning can also lead to increased foliar nutrient concentrations, due to the greater availability of nutrients to the remaining trees. Medhurst and Beadle (2005) found that photosynthetic rate was positively related to foliar N concentration, which increased following thinning of *E. nitens*. Gauthier and Jacobs (2009) showed that foliar N of *Juglans nigra* also significantly increased in thinned trees. These studies have found that increased foliar nutrients after thinning led to a reduction in specific leaf area (SLA) that underpinned the increase in A_{max}. In the current study, SLA of thinned treatments was lower than unthinned treatments, and nutrient concentrations (N and P) were significantly higher in the thinned and in the P-fertilised treatments than in unthinned and unfertilized treatments.

Forrester et al. (2012b) found that thinning increased A_{max} in the absence of fertiliser application but that A_{max} decreased when *E. nitens* were both thinned and fertilised. The decrease of A_{max} in the thinned and fertilised treatment was associated with decrease of stomatal conductance, but the authors were unclear on the mechanism for this observation. They proposed that an investigation of stomatal conductance and leaf biochemistry after the combined thinning and N fertiliser application may help to explain the mechanism behind such a response. The stronger response of A_{max} to thinning than to P fertiliser in our study suggests that light was more limiting than nutrients in the photosynthetic processes in thinned *A. auriculiformis* plantations, although there was still a foliar response to P, either with or without thinning.

Litterfall of thinned plots was lower than in unthinned plots up to three years after thinning, due to the greater longevity of leaves at the bottom of the canopy. However, these differences were only signficant from three to eight months after thinning and subsequently during the two driest months of the dry season. Similarly, Kunhamu et al. (2009) reported a strong positive relationship between litterfall and stand basal area of thinned *A. mangium* plantations. Litter production also varies among species and growing seasons. In the present study, annual litterfall of the *A. auriculiformis* plantation was within the range (5.7 – 12.5 Mg ha^{-1} yr^{-1}) previously reported for *A.* hybrid (Huong et al. summited, Chapter 5) and *A. mangium* plantations (Kunhamu et al. 2009). The peak in *A*. hybrid litterfall production in the dry season was associated with water stress (Huong et al. submitted, Chapter 5), supporting the theory that the thinned trees had lower water stress than the unthinned trees, especially in the dry season, when the differences between thinned treatments were most pronounced.

Immediately after thinning, stand leaf area index (LAI) of *A. auriculiformis* plantations was reduced, commensurate with the removal of stem volume. However, during the course of the study, LAI in the thinned plots increased consistently while LAI of unthinned plots decreased slightly except in December 2013. Increasing LAI in thinned stands is likely to have been as a result of growth of foliage on existing branches in the lower section of the crown (Medhurst and Beadle 2001, Forrester and Baker 2012) whereas reduction of LAI in unthinned plots has been found to be as a consequence of lower branch self-pruning and/or self-thinning (Guiterman et al. 2012).

Three years after thinning and P fertilizer addition, stem diameter of the *Acacia auriculiformis* plantations had a significantly greater mean diameter (ca. 3 cm) compared to the control. Similar responses to thinning and fertiliser treatments were found in temperate plantations such as *Eucalyptus nitens* (Forrester et al. 2012a) and *Pinus contorta* (Brockley 2005). While other systems have responded to nutrient addition at thinning, our study found that addition of P fertiliser in either thinned or unthinned treatments did not significantly improve tree growth. This suggests that light and/or water were the key factors limiting tree growth at age four years; and while application of P fertiliser did stimulate crown development (assessed as increased LAI and litterfall production), this did not flow through to an increase in diameter. The lack of responses to retention of thinning residues at the site is probably related to the lack of response to nutrients, and the fact that the residues can only contribute around 6.0 kg P ha^{-1}, over around the 24 months that it takes for the residues to fully decompose. However, much of the nutrient capital of the slash is in the leaves, which decompose faster than this. The lack of response to nutrients at this stage of growth contrasts with the response observed at establishment (Huong et al. 2015).

In this study, there was a marked reduction (> 50%) in diameter current annual increment (CAI) in all treatments three years after thinning. The rate of growth was directly related to photosynthetic rates and foliar P concentration, as measured at age seven weeks and one year after thinning, as well as the increased intra-specific competition within stand. The cause of similar growth decline in *Eucalyptus saligna* was found by Ryan et al. (2004) to be related a reduction gross primary production (GPP) caused by changing stand physiology and structure, and that the impact on wood production was more than for GPP alone because partitioning to wood was lower (Binkley et al. 2004, Ryan et al. 2004).

While the thinning treatment at 4 yr necessarily resulted in a proportional volume loss, greater CAI in the remaining stand resulted in standing volumes in the thinned treatments somewhat catching up, such that the volumes were not significantly lower than in unthinned treatments at seven years. A thinning operation at age four years offers an opportunity for growers to improve their cash-flow if they can sell their thinnings for pulpwood at a profit. There was no significant difference in the total value of wood harvested at age seven years between unthinned and thinned treatments, because of the higher proportion of large saw-logs recovered from the thinned treatments, so there is scope for the farmer to return a higher net profit. Similarly, Beadle et al. (2013) reported that at age 4.5 years, two years after thinning of an *Acacia* hybrid plantation in Dong Hoi, Vietnam, the percentage of saw-log significantly increased from 6.7% in unthinned (871 trees ha^{-1}) to 22.4 % in thinned treatments (450 trees ha^{-1}). Therefore, saw-log products from thinned acacia plantations may contribute more materials for sawmills and have positive impacts for wood trading in Vietnam. While the economics of a sawlog rotation look promising from this study, it needs to be recognised that a full discounted cash flow analysis which accounts for the relevant input costs and also farmer needs and motivations should be conducted before such a regime can be recommended.

4.5. Conclusion

Thinning to 833 trees ha^{-1} from an initial planted density of 1667 trees ha^{-1} of *Acacia auriculiformis* at age four years significantly affected a number of physiological processes, including an increased photosynthetic rate (A_{max}), relative to the unthinned control, for at least one year after thinning, and increased foliar N and P concentration one and two years after thinning, respectively. Leaf area index (LAI) in thinned treatments was lower than, but increased relative to, unthinned treatments during the course of the study, such that the differences were not significant by 20 months after thinning. Nine months after thinning, there were no significant differences in litterfall between thinned and unthinned treatments, except in the driest months (January, February 2014 and January 2015). Combined thinning and 50 kg P ha^{-1} application increased A_{max}, but A_{max} was not significantly influenced by P fertiliser application in unthinned treatments. Retention of slash and litter at thinning time tended to be associated with increased tree growth rate, but the effect was not significant. By age seven years, stem diameter in thinned treatments was significantly higher than in unthinned treatments. Recovery of higher value log sizes in thinned treatments was also significantly higher than in unthinned treatments, such that the total value of wood products standing at age seven years was higher in the thinned treatments (including the thinning harvested in year 4) than the unthinned treatments, although a more detailed economic analysis is needed to quantify the value of a sawlog regime to farmers.

Chapter 5. Growth and physiological responses to intensity and timing of thinning in short rotation tropical *Acacia* hybrid plantations in South Vietnam

Vu Dinh Huong[1,2,3*], Daniel S. Mendham[2] and Dugald C. Close[3]

[1]Forest Science Institute of South Vietnam, Ho Chi Minh City, Vietnam

[2]CSIRO Land and Water, Private Bag 12, Hobart, Tasmania 7001, Australia

[3]Tasmanian Institute of Agriculture, School of Land and Food, University of Tasmania, Private Bag 98, Hobart, Tasmania 7001, Australia

*Corresponding author, e-mail: Huong.VuDinh@utas.edu.au

Abstract

Acacia hybrid plantations are widely planted in Vietnam initially for wood chip production. However, these plantations have the potential to be managed for production of high value saw-logs. This study examined the growth and physiological responses to thinning treatments of different intensities at age two and three years. Treatments included: unthinned (planting density of 1111 trees ha^{-1}), moderate thinning (to 800 trees ha^{-1}) and intensive thinning (to 600 trees ha^{-1}) in a single thinning at either age two or three years, and one treatment that was progressively thinned from 1111 to 833 trees ha^{-1} at age two, and then to 600 trees ha^{-1} at age three years. Three years after intensive thinning at age 2 yr the average stem diameter was increased by 16.7 % and the stand volume was reduced by 15.8%. The moderate thinning regime resulted in no significant loss in stand volume and increased the average diameter by 7.5%. After thinning, LAI of intensively thinned stands recovered rapidly and there was no significant difference between unthinned and thinned treatments at 1 yr after thinning that was associated with a reduction in litterfall. Intensive thinning increased photosynthetic rates of the lower crown by 30.4 % in association with increased phosphorus concentration in the leaves of 37.5 %. Thinning reduced leaf water stress during the dry season through leaf water potential and tree growth were significantly influenced by season. We found that thinning of *Acacia* hybrid at age 2 or 3 yr resulted in higher leaf-level photosynthesis, enhanced water relations, and improved foliage phosphorus relative to unthinned trees, suggesting that intensive thinning at age two years or moderate thinning at age three years are likely to confer greater benefit to acacia growers. However, adoption of these management approaches should consider the market value of different log sizes and the risks associated with managing for saw-logs, including longer rotations.

Key words: *Acacia* hybrid, moderate and intensive thinning, photosynthesis, litterfall and LAI

5.1. Introduction

Acacia plantations cover approximately 2.6M ha in South-east Asia; >1M ha are in Vietnam (Harwood and Nambiar 2014). These are typically grown on short rotations of 5 – 8 yr to supply wood for pulp and paper production. However, about 65% of the approximately 10M m^3 of timber that is used to produce furniture, much of it acacia timber, is imported, so ways to increase the amount of sawlogs produced from Vietnam's own plantation resources are being sought (AGROINFOR 2014). For tropical acacias, planting densities ≥1000 trees ha^{-1} are required to encourage good apical dominance and tree form, so management for large diameter logs (>20 cm small-end diameter under-bark) will require a lower final stocking density (Beadle et al. 2013).

Thinning is the most common intervention that is used to increase the size and value of harvested trees. Interventions connected with stand management not only affect tree growth but can also lead to physiological changes (Kozlowski and Pallardy 1997c). Thinning redistributes site resources (light, water and nutrients) to the more valuable trees and reduces intraspecific competition for these resources; this is associated with increased rates of canopy and root-system development, and results in faster growth rate of the remaining trees and the opportunity for shortening the rotation (Smith 1986, Evans and Turnbull 2004, Forrester 2013, West 2014).

Thinning regimes need to consider intensity and timing as well as frequency and final stocking; intensity and timing may also determine the thinning response (Bredenkamp 1984, Evans and Turnbull 2004, Forrester 2013, West 2014), and their correct application is likely to be crucial if responses are to be optimised for fast-growing species like *Acacia* hybrid. Early-age thinning minimises intra-specific competition for resources which can develop rapidly in such plantations (Bredenkamp 1984). Conversely, later-age thinning is more likely to be commercial, reduce the cost of weed control and improve tree form (Evans and Turnbull 2004), but result in smaller responses to thinning as growth rates decline with the intensification of intra-specific competition. Thinning intensity must be linked with thinning time and the purposes of forest management (Evans and Turnbull 2004). However, a thinning intensity that attempts to maximise competition-free growth may result in reduced yield (Bredenkamp 1984) which must be compensated for by higher wood value. For *Eucalyptus grandis* Hill ex Maiden plantations in South Africa, to maintain a final yield of >30 $m^3\ ha^{-1}yr^{-1}$, it was recommended that thinning should start as early as age 3 yr with a thinning frequency of 2-to-5 years to stockings between 56 – 358 trees ha^{-1} for clearfelling between 15 – 30 yr (Schönau 1981, Schönau and Coetzee 1989). In Vietnam, low-income smallholders account for over 50% of the domestic wood supply (Beadle et al. 2015) and much shorter rotations for saw-log production will be required to make them an attractive investment. How to rapidly maximise wood yield and value of *Acaci*a hybrid plantations managed for sawlogs therefore needs to be resolved.

Thinning has the potential to increase photosynthetic rate, and light- and water-use efficiencies (Wang et al. 1995, Medhurst and Beadle 2005, Gauthier and Jacobs 2009, Forrester et al. 2012b). Medhurst and Beadle (2005) reported significant increases in light-saturated net photosynthetic rates in the lower and middle crown zones of plantation *Eucalyptus nitens* (Deane & Maiden) Maiden following thinning, and increased foliar nitrogen and phosphorus content due to a significant decrease in specific leaf area after thinning. The amount of light intercepted expressed as absorbed photosynthetically active radiation (APAR), and light-use efficiency are among the factors that explain the rate of growth of young trees, with growth tending to increase linearly with APAR (Forrester et al. 2013). Thinning of closed-canopy stands is expected to increase the APAR of retained trees (Wang et al. 1995); hence their higher growth potential (e.g. *B. papyrifera*, Wang et al. 1995; *E. nitens*, Medhurst and Beadle 2005; Forrester et al. 2013). Increases in amount of available soil moisture following thinning can be associated with a decrease in individual tree water stress because of reductions in stand-level transpiration and losses from rainfall interception (White et al. 2009), and increased water-use efficiency (Forrester et al. 2012b).

The size, geometry and spatial distribution of the canopy also influence the amount of photosynthetically active radiation (PAR) intercepted by leaves (Beadle 1997); how much is intercepted is determined by its leaf area index (LAI) (Landsberg and Sands 2010b). Positive relationships are observed between LAI and biomass production (Beadle et al. 1982, Smethurst et al. 2003). Reductions in LAI are determined by the intensity of thinning, but rates of increase of LAI may be independent of residual stocking; however residual stocking can have a strong effect on leaf area increase per tree which is correlated with changes in crown length (Medhurst and Beadle 2001). A contributory factor in this recovery of LAI is a reduction in litterfall production which decreases with thinning intensity and resulted in a significant relationship between annual litterfall and basal area in thinned *Acacia mangium* plantations (Kunhamu et al. 2009).

Many commercial species have been thinned in order to increase stem diameter growth and potential value of the retained trees (Medhurst et al. 2001, Kanninen et al. 2004, Mäkinen and Isomäki 2004, Simard et al. 2004, Cassidy et al. 2012, Forrester and Baker 2012, Beadle et al. 2013). For *Acacia* hybrid plantations in central Vietnam, reducing stand density from 871 trees ha^{-1} to either 600, 450 or 300 trees ha^{-1} at age 2.5 yr led to significant increases in the diameter increment of retained trees, though there were no significant differences in periodic basal area increment between treatments 18 months after thinning; a reduced total volume of wood grown by age 4.5 yr in the thinned treatments was associated with a rapid increase in saw-log values (Beadle et al. 2013). However, most of the detailed plantation-based thinning research has focused on eucalypts (Schönau and Coetzee 1989, Forrester 2013) and pines (Tang et al. 2003, Mäkinen and Isomäki 2004) and as yet, the underlying growth and physiological responses of tropical acacias to the intensity and timing of thinning have received relatively little attention. The objectives of this study were to: (1) quantify growth responses of *Acacia* hybrid plantations following thinning at different intensities and times, and (2) interpret these responses in the context of changes in photosynthetic rate (A), leaf area index (LAI), litterfall, specific leaf area (SLA), nutrient uptake and levels of water stress.

5.2. Materials and Methods

5.2.1. Location, climate and soils

The site was located in South Vietnam at Phu Binh (11.3° N, 106.8° E). The region has a mean annual maximum temperature of 35.6°C, mean annual minimum temperature of 21°C and annual rainfall of 2 800 mm $y^{\mathbf{-1}}$ with a marked dry season, typically from December to March (Figure 5.1). The soil type is a Chromic Acrisol, with a sandy clay loam A horizon, grading to a sandy clay B horizon. Soil sampled before planting had the following properties at 0 - 20 cm depth: bulk density 1.35 (± 0.01) g cm^{-3}, clay 26.2 (± 0.4) %, pH (H_20) 4.47 (± 0.04), pH (KCl) 3.92 (± 0.03), soil organic carbon (SOC) 19.9 (± 0.1) g kg^{-1}, total nitrogen (N) 1.14 (± 0.05) g kg^{-1} and Bray-1 extractable phosphorus (P) 7.8 (± 0.4) mg kg^{-1}.

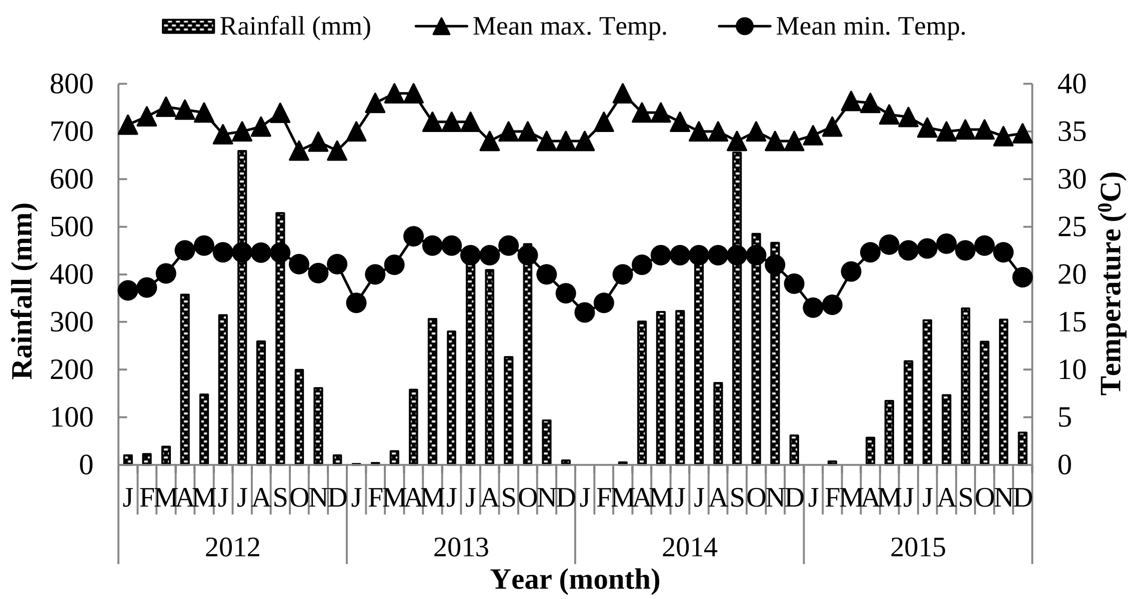

Figure 5.1 Mean monthly temperatures (minimum and maximum) and monthly rainfall during the study period (Source: Dong Xoai Meteorological station located 20 km from the experimental site).

5.2.2. Stand history

This site previously carried two rotations of *Acacia auriculiformis* plantations. For this study, remits of *Acacia* hybrid Clone AH07 (Nghia et al. 2010) were planted in July 2010 on a square grid at 3 m × 3 m spacing (equivalent to 1111 trees ha^{-1}). Fertiliser was applied at planting, with each tree receiving 100 g NPK (16 - 16 - 8) plus 403 g superphosphate fertiliser (7.2 % P) that was equivalent to 50 kg P ha^{-1}, 17.8 kg N ha^{-1} and 8.9 kg K ha^{-1}. Although the incidence of multi-leadering after planting was low (< 5%), tip pruning i.e. the removal of half the length of potentially competing stems and branches, was applied at ages 3, 6 and 12 months to ensure the development of single stems. All trees were lift pruned to 2.5 m height at age 18 months. Weeds were controlled by spraying with glyphosate (1.92 kg ha^{-1}) before planting and annually up to age four years.

5.2.3. Experimental design

Six thinning treatments (see Table 5.1) were applied to plots in each of three replicates in a randomised block design. The treatments were as follows: 1111 trees ha^{-1} (un-thinned control, T1); thinned to 833 trees ha^{-1} at age 2 yr (July 2012; T2); thinned to 600 trees ha^{-1} at age 2 yr (T3); thinned to 833 trees ha^{-1} at age 2 yr, and then to 600 trees ha^{-1} at age 3 yr (June 2013; T4); thinned to 833 trees ha^{-1} at age 3 yr (T5); and thinned to 600 trees ha^{-1} at age 3 yr (T6). The gross size of each plot was 24 × 24 m (8 × 8 trees), with 1 buffer row, resulting in a net (measured) plot size of 18 × 18 m (6 × 6 trees).

5.2.4. Measurements

5.2.4.1. Stand growth

Tree diameters over bark at breast height (*DBH* at 1.3 m) and heights (*H*) of all trees in net plots were measured just before each thinning and then approximately every six months during the experiment.

Stem growth rates of two randomly selected trees in five treatments: T1, T2, T3, T5 and T6 were assessed using band-dendrometers (DRL26, ICT International Pty Ltd) fitted at 4 m height above ground. Data were recorded hourly and collected monthly; the instrument had a measurement resolution of 1 μm in stem diameter change.

Total stand volume was estimated from *DBH* using an allometric regression relationship between *DBH* (X in cm) and standing volume (V in m^3):

(5.1) $V = 0.00009X^{2.8028}$ ($R^2 = 0.94, n = 50$). This equation was developed by felling and assessing 50 trees from age two to five years with diameters that ranged between 8 and 18 cm. A common volume equation was used as there were no significant differences between stand ages and thinning intensity treatments.

5.2.4.2. Leaf area index

Leaf area index (LAI) was measured in all treatments by using a Nikon Coolpix L29 Digital Camera (Nikon Camera, Japan) at three-monthly intervals after the early thinning. To facilitate these measurements, 10 stakes were placed in two parallel lines diagonally through the middle of each plot. This arrangement was designed to capture any heterogeneity in the distribution of the canopy in space, particularly in the thinned plots. To estimate LAI, the digital photographs were analysed using Fiji-win32 image analysis software, with an automated thresholding algorithm to convert to black and white, and extraction of the gap fraction as the proportion of white in the image. The gap fraction was converted to an estimate of LAI using Beers law of light extinction. These digital camera estimates of LAI were calibrated against measures of plant area index (PAI) made in April and July 2014 at the same points using a Li-Cor LAI-2000 Plant Canopy Analyser

(5.2) $(PAI = 0.808LAI_{camera} + 0.2869\ [R^2 = 0.99; n = 36; P < 0.001])$ and

PAI converted to actual LAI using an equation developed by Battaglia et al. (1998)

(5.3) $(LAI = 1.54PAI - 0.11\ (R^2 = 0.99)$).

5.2.4.3. Litterfall collection

Two 1 m^2 area litter traps were placed at random locations within each plot of the T1, T2 and T3 treatments after the first thinning and for the T5 and T6 treatments after the second thinning. Litter was collected at monthly intervals for a period of either one (T5, T6) or two (T1, T2, T3) years.

5.2.4.4. Gas-exchange measurements

Gas-exchange of leaves was measured four weeks after the early thinning at age 2 yr; four trees were randomly selected in each of the T1 and T3 treatments. Further measurements were undertaken six weeks after the late thinning at age 3 yr; on this occasion three trees were randomly selected in each of the T1, T3 and T6 treatments. For sampling, the live crown depth was equally divided into an upper and lower zone. At each sampling time, small branches, two at the age 2 yr and one at age 3 yr, were collected from the sunlit side of each crown zone of each tree in each treatment plot. The cut ends were placed immediately in a bucket and re-cut under water to avoid embolism (Turnbull et al. 2007, Eyles et al. 2011). One newly fully-expanded leaf from each branch was selected for measurement. For the sampling at age 2 yr and 3 yr, a total of 32 and 18 leaves, respectively were assessed at each time during the diurnal time-course.

Photosynthesis was measured by using a Li-Cor LI-6400 portable open-path gas-exchange system (Li-Cor Inc., Lincoln, NE, USA) with a standard 20 × 30 mm chamber equipped with blue-red light emitting diodes mounted on the top of the chamber (Model 6400-02B).

Diurnal rates of light-saturated net photosynthesis (A_{1500}) and stomatal conductance (g_s) were determined at approximately 2.5 h intervals between 06:30 and 18:00 h local time at 1500 μmol m^{-2} s^{-1} of photosynthetically active radiation (PAR) and an ambient CO_2 partial pressure (C_a, μmol CO_2 mol^{-1} air) of 400 µmol s^{-1}.

Photosynthetic light response curves (A/Q) were constructed using leaves collected at the same time as for the diurnal gas-exchange measurement (see above). In the 2-yr sampling, leaves were collected between 09:00 h and 14:00 h from 4 trees from each of the 2 treatments (T1 and T3) and 2 canopy heights (n = 16) while for the 3-yr sampling, leaves were collected during the same time interval, but from 3 trees in each of 3 treatments (T1, T3 and T6) and 2 canopy heights (n = 18). A fixed C_a of 400 ppm was used in all of the light response curves. The quantum flux (Q) was reduced in nine steps from 2000 μmol m^{-2} s^{-1} to darkness with the following sequence of PAR: 2000, 1500, 1000, 650, 300, 200, 100, 50 and 0 μmol m^{-2} s^{-1}.

Following completion of gas-exchange measurements, the used leaf samples were sampled and placed into zip-lock plastic bags, stored on ice prior to refrigeration and then assessed for specific leaf area (SLA, cm^2 g^{-1}). To measure leaf area, leaves were scanned and images analysed using Image J v1.37 (Abramoff et al. 2004). They were then dried for N and P analysis (see below). Leaf N and P concentrations (mg g^{-1}) and contents (mg cm^{-2}) were calculated on an air-dry mass basis.

5.2.4.5. Nutrient analysis

The dried samples were weighed and ground in a hammer mill to $\leq$ 0.02 mm. Subsamples (~0.5 g) were digested in concentrated sulphuric acid and 30% hydrogen peroxide. Nutrient concentrations were measured in the digest according to methods of Rayment and Higginson (1992), as adapted by the Forest Science Institute of South Vietnam: Nitrogen was analysed using the standard N-Kjeldahl method and phosphorus determined by an ANA-720W spectrophotometer (Tokyo Photo-electric Company Limited, Japan).

5.2.4.6. Leaf water potential measurement

Leaf water potential (Ψ_{leaf}) was measured in the T1, T2 and T3 treatments at three-month intervals after the early-age thinning using a Scholander 40-bar (4 MPa) pressure chamber (PMS Instruments Co., Corvallis, Oregon, USA). The measurements were taken at approximately 2.5-h intervals from 05:00 (pre-dawn; Ψ_{pd}) to 17:00 h local time. The measurement at 11:00 h is referred to as the midday water potential (Ψ_{md}).

For each sampling time, three trees were randomly selected within the treatment plot. From each tree, three branches of 10-20 mm diameter in the lower crowns were selected and excised. One newly fully-expanded leaf from each branch was collected, placed immediately into a sealed plastic bag, and kept in a cool box in the dark until measurements were made within 10 min of excision.

5.2.4.7. Leaf carbon and nitrogen isotope analysis

In March 2013, eight months after the first thinning, leaf samples from 27 trees of T1, T2 and T3 treatments were collected for leaf carbon and nitrogen isotope analysis. Each treatment had nine selected trees from the three plots and each plot had three selected trees: one tree represented the mean tree, one of +1 standard deviation (SD) and one of -1 SD, based on diameter and height. Twenty fully expanded leaves per tree from the middle crown zone were sampled. Leaf samples were dried at 65º C for 48 h to constant weight before sub-sampling for isotope analyses.

Carbon and nitrogen isotope composition ($\delta^{13}C$ and $\delta^{15}N$) were assessed using a continuous flow mass spectrometer (Micromass Isochrom). ^{13}C:^{12}C ratios of the CO_2 produced by combustion at 1000ºC in an oxygen atmosphere were then compared against those obtained by combustion of Beet sugar (-26.1) and Australian National University Sucrose (-10.45), calibrated in turn against the international standard NBS-22. Analytical precision was based on multiple replicate analyses for $\delta^{13}C$ (± 0.2 ‰) relative to the PeeDee Belemnite standard (Coplen 1988). ^{14}N:^{15}N ratios were compared against those obtained by combustion of internal standards of Alanine (-1.57), gelatine (7.63) and sealine (2.25), calibrated in turn against the international standards for caffeine and L-glutamic acid and the Oxford University Alanine (refer to Australian National University Laboratory 2013).

5.2.5. Statistical analysis

Analysis of variance was used to test the variance in tree growth and tree physiological parameters between treatments. Whenever the ANOVA indicated a significant difference between means (P < 0.05), these were compared using least significant difference (*LSD*) in a multiple range test. The effect of time on the diurnal patterns of gas exchange and Ψ_{leaf} were tested by repeated measures ANOVA. The effects of time, thinning and crown on light-saturated net photosynthesis (A_{1500}, μmol m^{-2} s^{-1}), stomatal conductance (g_s, mol m^{-2} s^{-1}), light saturated photosynthesis rate (A_{max}, μmol m^{-2} s^{-1}), apparent dark respiration (R_{dark}, μmol m^{-2} s^{-1}), nitrogen concentration (mg g^{-1}) and phosphorus concentration (mg g^{-1}) were evaluated with a statistical model appropriate for a split-split plot experiment. Time was the whole-plot factor, treatment and replicate were used as sub-plot factors and crown height a sub-sub-plot factor. A non-rectangular hyperbolic function was used to examine the relationship between photosynthetic rate and PAR (Sands 1995) and to estimate apparent quantum yield (Φ), A_{max} and R_{dark}. Linear regression analyses were used to examine the relationships between rainfall summed three months prior to measurement and Ψ_{pd} and Ψ_{md} as well as the relationship between A_{1500} and foliar phosphorus concentration. All analyses were conducted by using Genstat 13th Edition (VSN International 2011).

5.3. Results

5.3.1. Tree growth and survival

Just before the early-age thinning at age 2 yr, mean survival rates (%) were 94.4, 87.0, 84.3, 89.8, 88.0 and 93.5 in the T1, T2, T3, T4, T5 and T6, respectively; there were no significant differences between treatments. At the end of the experiment at age 5 yr, mortality across treatments was < 2% and unaffected by thinning treatment.

Immediately before and after the early-age thinning, there were no significant treatment differences in *H* or *DBH*; after thinning these were, on average, 9.9 m and 10.0 cm, respectively. At age 3 yr, T3 and T4 but not T2 had significantly greater current annual *DBH* increments than T1; T5 and T6 before thinning had similar increments to T1 (Table 5.1).

Immediately after the later-age thinning at age 3 yr, there were no significant differences between the newly thinned treatments (T4-T6) in which ranged from 12.2 to 12.3 cm. At age 4 and 5 yr, annual *DBH* increments in T3, T4 and T6 were significantly greater than in T1, T2 and T5. At age 5 yr, increments in T2 and T5 were significantly greater than in T1. However, absolute increments in the 5th year were less than half those in the 4th year (Table 5.1). Early and late thinning also resulted in significant increases in green crown length in T3 and T6 at age 4 yr, and also in T2 at age 3 yr one year after thinning (Table 5.2). There were no differences between T1, T2 and T3 just before thinning.

At age five years in July 2015, *DBH* of the T3, T4 and T6 treatments were 16.1 ± 0.1, 16.0 ± 0.1 and 15.8 ± 0.1cm respectively, which were significantly greater than those in T2 (14.8 ± 0.2 cm) and T5 (14.9 ± 0.1 cm); the *DBH* of all thinned treatments were significantly greater than those of T1, 13.8 ± 0.1 (Table 5.1). The *H* of trees in T1 was also significantly lower than in the other treatments.

Table 5.1 Effects of time and intensity of thinning on diameter. Bold figures indicate increment after a thinning treatment. Different letters indicate means are significantly different at $P < 0.05$.

Treatments	Stocking	Diameter (cm)						Current annual diameter		
		Before		After thinning				After thinning		
	(trees ha^{-1})	Age 2	Age 3	Age 2	Age 3	Age 4	Age 5	Age 3 yr	Age 4 yr	Age 5
T1_control	1111	9.68^{a}	11.52^{a}	9.68^{a}	11.52^{ab}	13.18^{c}	13.80^{c}	1.84^{c}	1.66^{b}	0.62^{bc}
T2_thinned at age 2 yr	833	10.15^{a}	12.24^{a}	**10.23**^{a}	**12.24**^{a}	**14.08**^{b}	**14.83**^{b}	**2.01**^{b}	**1.84**^{b}	**0.75**^{b}
T3_thinned at age 2 yr	600	9.63^{a}	12.34^{a}	**9.99**^{a}	**12.33**^{a}	**15.02**^{a}	**16.10**^{a}	**2.34**^{a}	**2.69**^{a}	**1.08**^{a}
T4_thinned at age 2 & 3 yr	833/600	9.85^{a}	12.07^{a}	**9.96**^{a}	**12.16**^{a}	**15.00**^{a}	**16.04**^{a}	**2.20**^{ab}	**2.84**^{a}	**1.04**^{a}
T5_ thinned at age 3 yr	833	10.12^{a}	11.87^{a}	10.12^{a}	**12.15**^{a}	**14.12**^{b}	**14.88**^{b}	1.75^{c}	**1.97**^{b}	**0.76**^{b}
T6_ thinned at age 3 yr	600	9.83^{a}	11.55^{a}	9.83^{a}	**12.27**^{a}	**14.83**^{a}	**15.85**^{a}	1.72^{c}	**2.56**^{a}	**1.02**^{a}
P-value ($\alpha = 0.05$)		0.31	0.06	*0.53*	0.07	<0.001	<0.001	<0.001	<0.001	0.003
LSD ($P = 0.05$)		0.58	0.58	*0.68*	0.54	0.29	0.22	0.21	0.34	0.22

Table 5.2 Effects of time and intensity of thinning on green crown length. Different letters indicate means are significantly different at $P < 0.05$. See Table 1 for treatment codes and descriptions.

Treatment	Green crown length (m)		
	Age 2 yr	Age 3 yr	Age 4 yr
T1	6.47^{a}	7.79^{a}	9.01^{a}
T2	6.81^{a}	9.22^{b}	10.52^{ab}
T3	6.69^{a}	9.55^{c}	13.05^{c}
T5	-	-	10.05^{ab}
T6	-	-	10.93^{b}
P-value ($\alpha = 0.05$)	0.53	<0.001	0.006
LSD *($P = 0.05$)*	0.78	0.20	1.66

After the early-age thinning at age 2 yr, stand volume was similar in T1, T2, T4, T5 and T6 and ranged from 48 to 60 m^3 ha^{-1}; stand volume of T3 (34.1 m^3 ha^{-1}) was significantly lower (Figure 5.2). After the later-age thinning at age three years, volume of treatments T3, T4 and T6 were similar and significantly lower than those of T1, T2 and T5. At age 5 yr, there were significant differences in volume between the unthinned treatment (T1) and thinned treatments, except T5 (Figure 5.2).

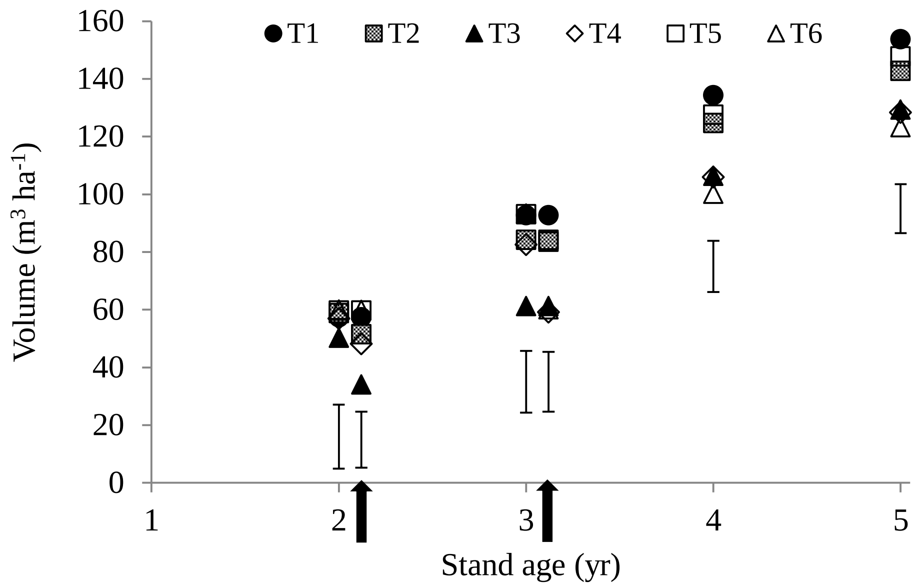

Figure 5.2 Effects of thinning on stand volume development of *Acacia* hybrid plantations. Vertical bars in the figure indicate LSDs at $P < 0.05$ for stand volume. Arrows indicated thinning times. See Table 5.1 for treatment codes and descriptions.

Across all treatments, monthly diameter increment decreased from August in the wet season to February in the dry season (Figure 5.3). Maximum increments were around 4 mm month^{-1} in August 2012 and declined with increasing tree diameter to around 2 mm month^{-1} in July 2014; minimum growth was around 0.0 mm month^{-1} and there was evidence of stem shrinkage (Figure 5.3). Significant differences in monthly growth increment occurred between treatments during the wet season only; generally, the ranking of increments was 600 > 833 > 1111 trees ha^{-1} (Figure 5.3).

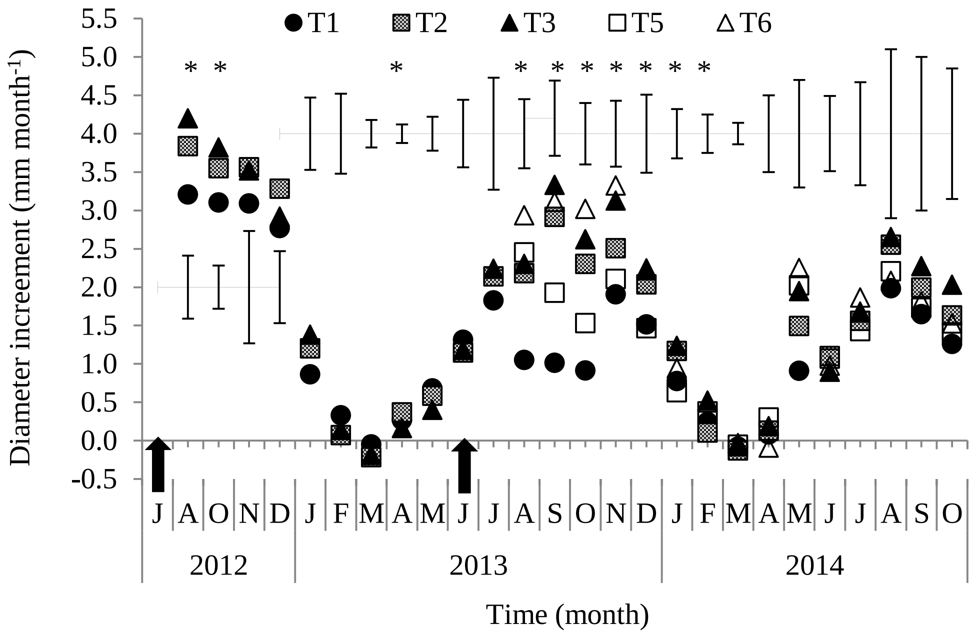

Figure 5.3 Effects of thinning treatments on monthly diameter increment of *Acacia* hybrid plantations. Vertical bars in the figure indicate *LSD*s at $P < 0.05$ for monthly diameter increment. Arrows indicate thinning times. Asterisks (*) indicate significance of treatments at $P < 0.05$. See Table 5.1 for treatment codes and descriptions.

5.3.2. Leaf area index

Immediately after the early-age thinning treatment, the leaf area index (LAI) of T1, T2 and T3 was significantly different ($P < 0.03$) and respectively 3.3, 2.7 and 2.1 $m^2\,m^{-2}$ (Figure 5.4). Their LAI increased throughout the remainder the wet season (until October) when T1, T2 and T3 were respectively 3.6, 3.4 and 2.7 $m^2\,m^{-2}$; there was no significant difference between T1 and T2; LAI of T1 remained significantly higher than T3. The LAIs then declined throughout the dry season. However, changes were less marked in the T3 than T2 and T1 treatments such that there were no differences between treatments in January 2013.

One year after the early-age thinning and one month after the later-age thinning (July 2013), LAI of T1and T2 were significantly higher than those of the other treaments, and T3 and T5 signifcantly higher than T6. In December 2013, T1 and T2 were significantly higher than T5; T6 was significantly lower than all other treatments. By July 2014, there were no significant thinning treatment effects on LAI (Figure 5.4).

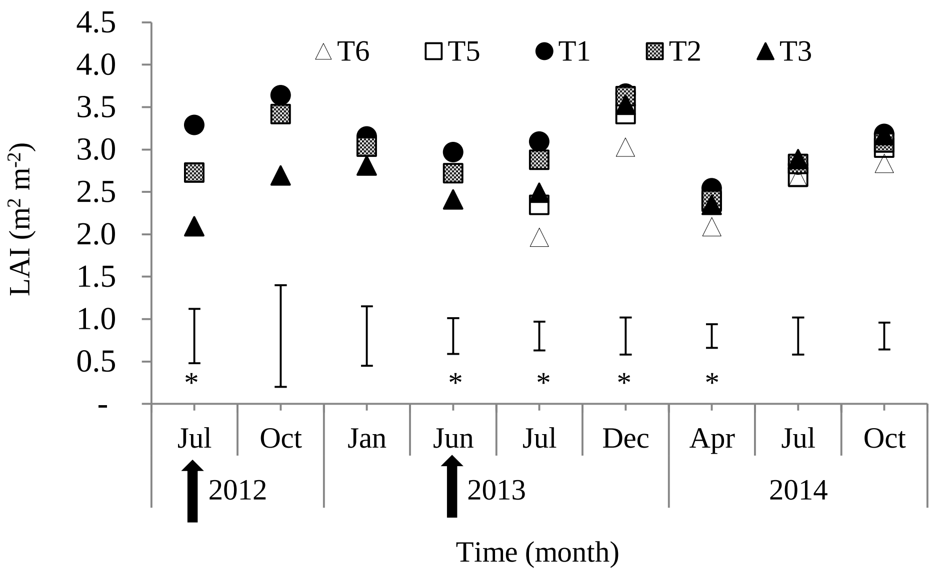

Figure 5.4 Effects of thinning treatments on leaf area index (LAI) from age 2 to age 4 yr. Vertical bars in the figure indicate LSDs at $P < 0.05$ for LAI. Arrows indicated thinning times. Asterisks (*).indicate significance of treatments at $P < 0.05$. See Table 5.1 for treatment codes and descriptions.

5.3.3. Litterfall production

Litterfall rates of all treatments were lower during the wet than the dry season (Figure 5.5). Three months after the early-age thinning (October 2012), litterfall production of T3 was significantly lower than T1 and T2. This difference remained significant until January

2013, except November 2012 when no significant difference between T2 and T3 was found. Following the later-age thinning by June 2013, litterfall of T5 and T6 was initially similar to the other treatments, but then significantly lower than that of T1, T2 and T3 between November and December 2013. There were subsequently no differences between treatments. The average values (Mg ha^{-1} month^{-1}) between age three and four years of T1, T2, T3, T5 and T6 were 1.02 ± 0.08, 1.02 ± 0.07, 1.05 ± 0.09, 0.92 ± 0.07 and 0.86 ± 0.06, respectively (Figure 5.5).

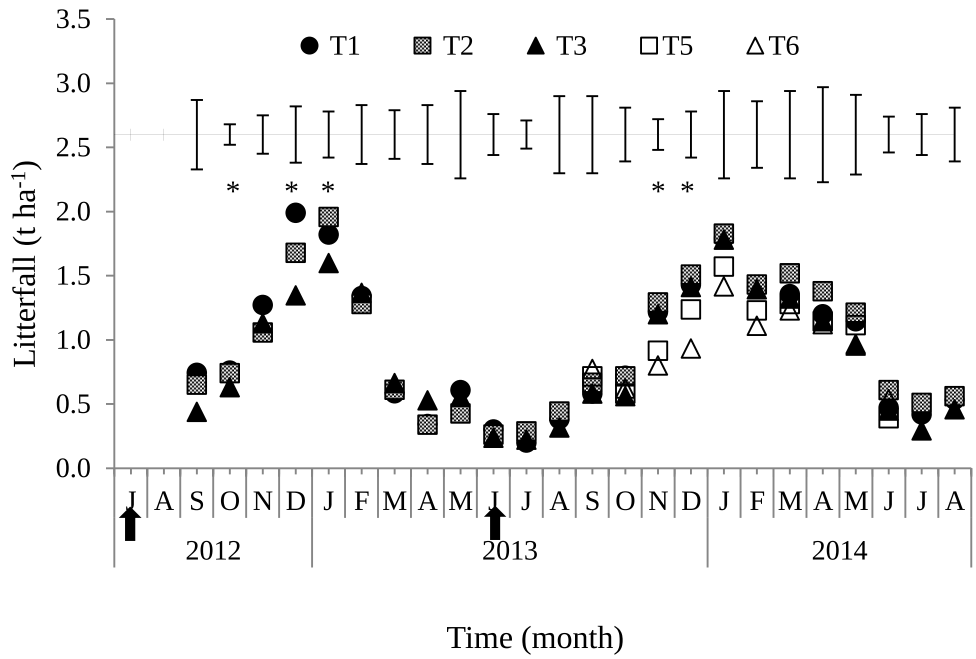

Figure 5.5 Effects of thinning treatments on litterfall production of *Acacia* hybrid plantations from age 2 to 4 yr. Vertical bars in the figure indicate LSDs at $P < 0.05$ for monthly litterfall production. Arrows indicate thinning times. Asterisks (*).indicate significance of treatments at $P < 0.05$. See Table 5.1 for treatment codes and descriptions.

5.3.4. Specific leaf area, and foliar nitrogen and phosphorus concentrations

There were no significant differences in specific leaf area (SLA) between crown zones and thinning treatments, although values were generally lower in the upper than lower crown, and following the later-age than the early-age thinning; SLA ranged from 55.3 ± 3.6 to 94.1 ± 5.8 $cm^2\ g^{-1}$. Foliar nitrogen concentration (N, mg g^{-1}) was also not significantly different between crown zones and thinning treatments; for the latter, N varied between 23.0 ± 0.7 and 25.5 ± 0.3 mg g^{-1}. Similarly, foliar N content (mg cm^{-2}) was not significantly affected by crown zone or thinning treatment.

There was a significant time × treatment interaction for foliar phosphorus (P) concentration and content, with significantly higher (P <0.001) foliar P in T3 (1.7 ± 0.2 mg g^{-1} and 2.1 ± 0.1 mg cm^{-2}) compared to T1 (1.4 ± 0.1 mg g^{-1} and 1.7 ± 0.1 mg cm^{-2}) at age 2 yr. However, by age 3 y, there were no significant differences in foliar P between unthinned treatment (T1) and thinned treatments (T3 and T6), though there was a trend for the mean foliar P concentration in T3 and T6 in the lower zone to be higher than in T1.

5.3.5. Gas exchange

After the early-age thinning, diurnal patterns of A_{1500} were significantly influenced by time of day (P < 0.001) increasing sharply from 06:30 h (13.6 ± 0.9 µmolm^{-2} s^{-1}) to 09:00 h (18.1 ± 0.9 µmolm^{-2} s^{-1}), and then rates were maintained until 14:00 h and thereafter decreased rapidly to 17:00 h (3.1 ± 0.9 µmolm^{-2} s^{-1}). Mean daily A_{1500} in T3 (13.2 ± 0.8 µmolm^{-2} s^{-1}) was significantly higher (P <0.05) than that in T1 (11.2 ± 0.8 µmolm^{-2} s^{-1}); however, at crown level; this difference was only significant in lower zone.

After the later-age thinning, A_{1500} followed a similar diurnal pattern, although mean A_{1500} in both crown zones was significantly lower in T1 and T3 (P <0.001) in 2013 than 2012. In 2013, there was also a significant difference (P < 0.01) in A_{1500} in the lower crown between unthinned (T1, 8.5 ± 0.4 μmolm^{-2} s^{-1}) and thinned treatments (T3, 10.5 ± 0.4 μmolm^{-2} s^{-1}and T6, 9.4 ± 0.4 μmolm^{-2} s^{-1}), but no differences between T3 and T6; A_{1500} in upper crown was not affected by thinning.

Diurnal patterns of stomatal conductance (g_s) followed a similar pattern to those for A_{1500}. However, as for A_{1500}, mean values were higher after the early-age (T1 = 0.64 ± 0.06 and T2 = 0.65 ± 0.08 mol m^{-2} s^{-1}) than later-age (T1 = 0.36 ± 0.09, T3 = 0.45 ± 0.06 and T6 = 0.40 ± 0.08 mol m^{-2} s^{-1}) thinning. There were no significant differences in g_s between tretaments or crown zones.

For the light response curves, there was a significant time effect (P = 0.012) on mean net photosynthesis between 2012 and 2013 in the lower, 9.9 ± 0.6 μmol m^{-2} s^{-1} in 2012 and 7.6 ± 0.6 μmol m^{-2} s^{-1} in 2013, but not the upper, crown (Figure 5.6 a). When the data for T1 and T3 were pooled across 2012 and 2013, there were significant effects of both thinning treatment and crown zone on A_{max}, but no interactions; A_{max} in T3 (25.3 ± 1.9 μmol m^{-2} s^{-1}) was significantly greater (P = 0.021) than that in T1 (20.1 ± 1.9 μmol m^{-2} s^{-1}); and A_{max} was significantly greater in the upper (24.4 ± 1.9 μmol m^{-2} s^{-1}) than lower (20.9 ± 1.9 μmol m^{-2} s^{-1}) crown. Thinning (T3) increased A_{max}, relative to T1, in the lower crown by 36.7 % and 22.2 % in 2012 and 2013, respectively. When the 2013 data included T6, mean net photosynthesis was significantly (P = 0.004) lower in T1 (6.9 ± 0.5 μmol m^{-2} s^{-1}) than in T3 (8.3 ± 0.5 μmol m^{-2} s^{-1}) and T6 (8.2 ± 0.5 μmol m^{-2} s^{-1}) in the lower crown zone, but there were no significant differences between treatments in the upper crown zone (Figure 6 b). There was no effect of crown zone on A_{max}, although A_{max} was nearly significant higher (P = 0.07) in the upper than lower crown zone.

There were no significant differences between treatments in apparent quantum yield (Φ) for both early- and later-age thinning; mean Φ was 0.078 ± 0.07 μmol m^{-2} s^{-1}. When data was pooled across 2012 and 2013, dark respiration (R_{dark}) in T1 (0.74 ± 0.1 μmol m^{-2} s^{-1}) was significantly smaller (P = 0.02) than in T3 (1.20 ± 0.2 μmol m^{-2} s^{-1}); and significantly smaller (P = 0.006) for the lower (0.69 ± 0.1 μmol m^{-2} s^{-1}) than upper crown (1.26 ± 0.1 μmol m^{-2} s^{-1}); there were no significant interactions between year, thinning treatment and crown zone.

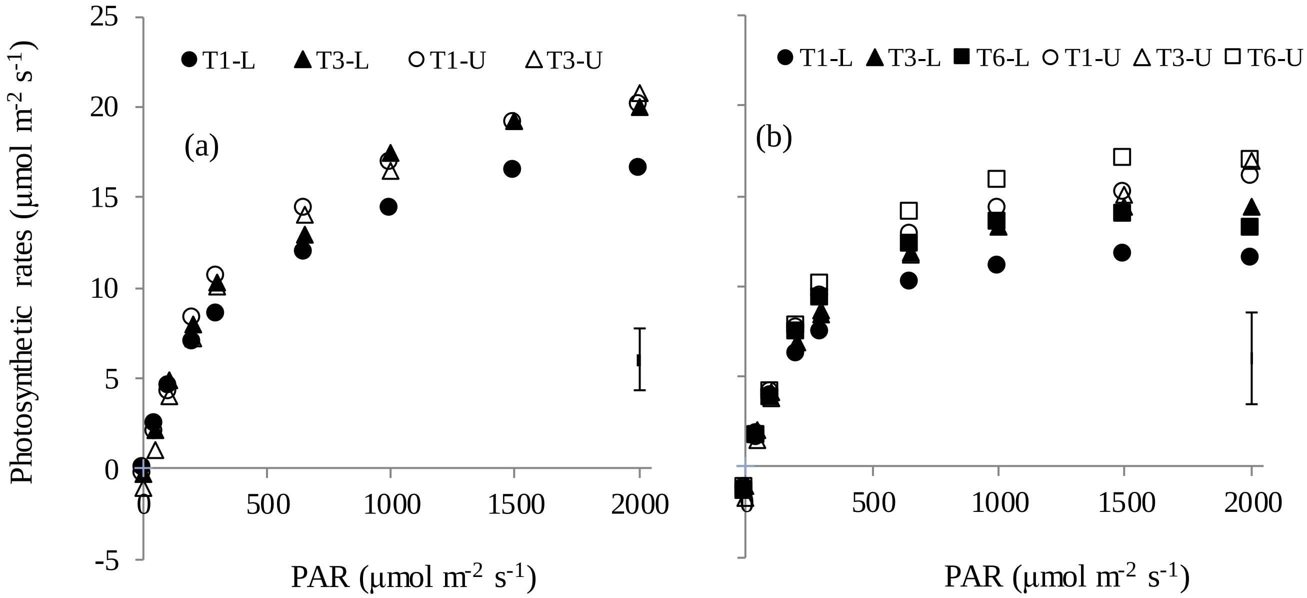

Figure 5.6 Photosynthesis light response curves of *Acacia hybrid* trees: (a) interaction data of four weeks after the first thinning in 2012 and six weeks after the second thinning in 2013 (T1, T3 and n = 28), and (b) six weeks after the second thinning in 2013 (T1, T3, T6 and n = 18). L = lower crown zone and U = upper crown zone. PAR = Photosynthetically active radiation. Error bars indicate least significant difference of interaction between treatments (LSD). Light-response curve parameters of apparent quantum yield (Φ), light-saturated photosynthesis (A_{max}) and dark respiration (R_{dark}) were estimated from the fitted non-rectangular hyperbolic functions of net CO_2 uptake versus PAR (Sands 1995). See Table 5.1 for treatment codes and descriptions.

There was a significant correlation (R^2 = 0.32, P = 0.0017, n = 28) between light-saturated net photosynthesis (A_{1500}) and foliar phosphorus concentration (P). Generally, higher levels of A_{1500} was associated with elevated foliar P levels in 2012 and vice versa in 2013. In addition, foliar P levels were higher in T3 than T1 in 2012 (Figure 5.7).

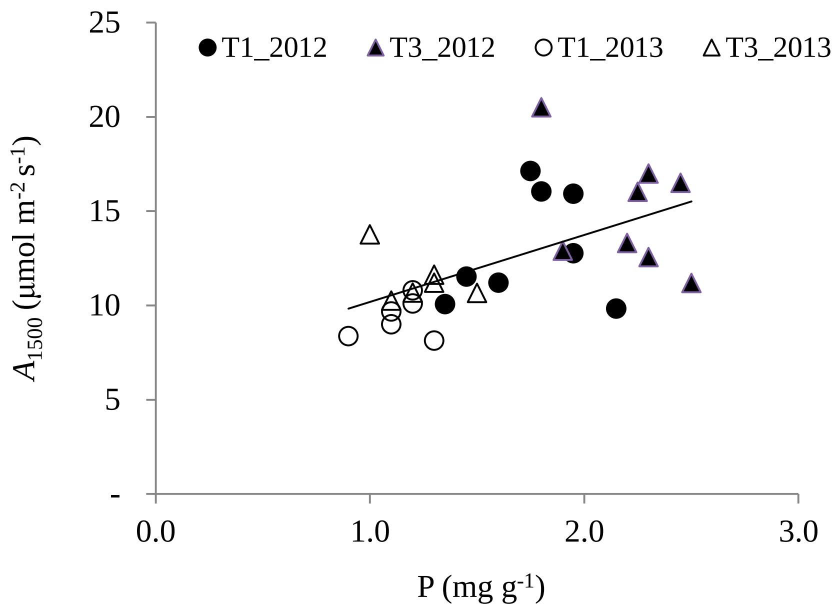

Figure 5.7 Relationship between mean light-saturated net photosynthesis (A_{1500}) and mean foliar phosphorus concentration (P) of unthinned treatment (T1) and thinned treatment (T3) in 2012 and 2013. The significant regression is $Y = 3.5571\ X + 6.6323$ ($R^2 = 0.32$; $n = 28$; $P = 0.0017$) where Y is A_{1500} (µmol m^{-2} s^{-1}) and X is P (mg g^{-1}).

5.3.6. Leaf water potential

The diurnal pattern of leaf water potential (Ψ_{leaf}) was significantly different between seasons (Figure 5.8a). In the wet season, mean pre-dawn water potential (Ψ_{pd}) across treatments was -0.24 ± 0.04 MPa; in the dry season it was -0.89 ± 0.07 MPa. In the wet season, maximum levels of water stress (-1.09 to -1.18 MPa) occurred at 11:00 h (Ψ_{md}) and Ψ_{leaf} recovered nearly to pre-dawn levels at 17:00 h just before sunset; in the dry season Ψ_{leaf} remained low between 11:00 and 14:00 h (-1.26 to -1.76 MPa) and recovered only to -

0.96 ± 0.03 MPa at 17:00 h (Figure 5.8a).

There was a strong relationship between Ψ_{pd} and Ψ_{md} and rainfall summed over the three months preceding measurement (Figure 5.8b). When the preceding 3-month rainfall was 26 mm, Ψ_{pd} and Ψ_{md} were respectively -1.02 ± 0.10, -0.87 ± 0.09 and -0.78 ± 0.08 MPa, and -1.58 ± 0.20, -1.66 ± 0.14 and -1.54 ± 0.12 MPa for T1, T2 and T3 (Figure 5.8b).

Thinning significantly increased Ψ_{leaf} in the wet (P = 0.04) and dry (P = 0.01) seasons. The mean diurnal values of Ψ_{leaf} for T1, T2 and T3 in the wet and dry seasons were 0.70 ± 0.08, -0.61 ± 0.07, -0.53 ± 0.07 MPa and -1.36 ± 0.08, -1.27 ± 0.08, -1.09 ± 0.07 MPa, respectively.

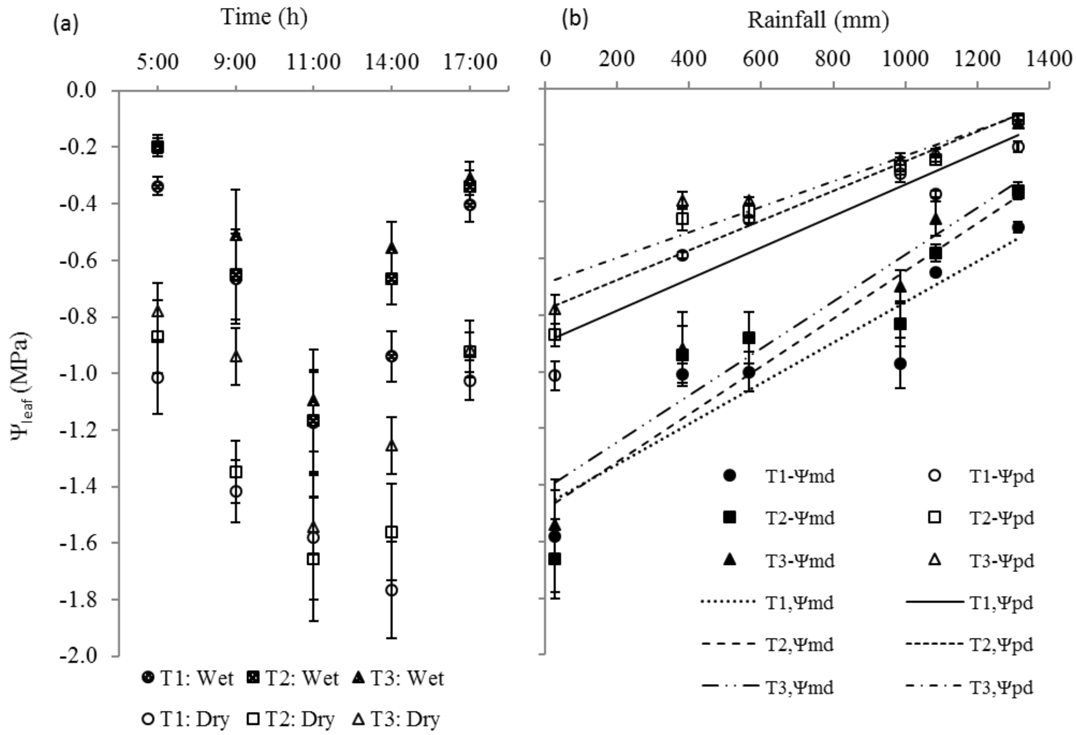

Figure 5.8 (a) Diurnal pattern of leaf water potential (Ψ_{leaf}) of *Acacia* hybrid trees one month after the early thinning in the wet season (17 August 2012) and in the dry season (27 February 2013). Error bars indicate means ± 1SE. (b) Relationships between pre-dawn (Ψ_{pd}) and midday (Ψ_{md}) leaf water potential and rainfall summed over the three-month period prior to measurement. The significant regressions (n = 6; $P < 0.01$) are: (T1,Ψ_{md}) $Y = 0.0007X - 1.4701$, $R^2 = 0.85$; (T2,Ψ_{md}) $Y = 0.0008X - 1.488$, $R^2 = 0.86$; (T3,Ψ_{md}) $Y = 0.0008X - 1.4124$, $R^2 = 0.92$, and (T1,Ψ_{pd}) $Y = 0.0006X - 0.8964$, $R^2 = 0.88$; (T2,Ψ_{pd}) $Y = 0.0005X - 0.7792$, $R^2 = 0.92$; (T3,Ψ_{pd}) $Y = 0.0004X - 0.6873$, $R^2 = 0.89$ where Y and X are Ψ_{leaf} (MPa) and rainfall (mm), respectively. See Table 5.1 for treatment codes and descriptions.

5.3.7. Carbon and nitrogen isotopes in leaf tissue

There were no significant differences between treatments in carbon isotope ($\delta^{13}C$) composition ($P = 0.67$); mean values of T1, T2 and T3 were -29.91, -30.01 and -30.22 ‰ respectively. Conversely, nitrogen isotope ($\delta^{15}N$) composition was significantly affected by thinning treatment ($P = 0.013$); T1 (3.29 ‰) was significantly lower than T2 (4.21‰) and T3 (4.43 ‰).

5.4. Discussion

5.4.1. Tree growth responses to thinning

Thinning from 1111 to 600 trees ha^{-1} resulted in significantly greater annual increments of diameter which were sustained for up to three years. Thinning is associated with increased resource availability to and reduced competition between the retained trees (Medhurst et al. 2001). This rapid growth response to thinning suggests that these levels of competition were such that the growth of individual trees was being slowed as early as age two years. Such thinning responses are often typical of fast-growing species such as eucalypts (Medhurst et al. 2001) and acacias (Kha 2001), and may occur following later-age (*Acacia mangium*, Kamo et al. 2009) as well as early-age thinning (*Acacia* hybrid, Beadle et al. 2013).

In contrast, thinning from 1111 to 833 trees ha^{-1} only resulted in a significantly greater first annual diameter increment, and only after the early-age thinning. A similar intensity of thinning, from 1413 to 1160 trees ha^{-1} in a *Tectona grandis* plantation at age 4 yr in Costa

Rica, had positive effects on diameter increment for two years only (Kanninen et al. 2004). The lack of a significant diameter response in *Acacia* hybrid to the later-age low-intensity thinning suggests that the response becomes lower the longer it is delayed (Bredenkamp 1984). However, a second thinning from 833 to 600 trees ha^{-1} at age 3 yr led to further significant responses to thinning which, as with a first thinning to 600 trees ha^{-1} at age 2 and age 3 yr were sustained until age 5 yr. Thus as found for fast-growing *Eucalyptus grandis* in South Africa (Schönau 1984, Smith and Brennan 2006), diameter responses can benefit from higher thinning intensities and earlier thinning times, as well as allowing longer intervals between thinnings, presumably because it takes much longer for the effects of intra-specific competition on individual tree growth to redevelop. Nevertheless, the initial response to thinning to 833 trees ha^{-1} still resulted in significantly greater tree diameters at age 5 yr than in the unthinned control.

There was a marked seasonal variation in monthly diameter increment, as well as a decline with tree size and stand age. In spite of substantial amounts of rainfall throughout the wet season, increments were cyclic, increasing to a peak in the middle of the wet season, and then declining to reach a minimum at the end of the dry season, which was close to zero. Significant responses to thinning treatment were therefore observed mainly in the wet season, even though trees in the thinned treatments were less water stressed in the dry season than unthinned trees. Worbes (1999) reported that the annual growth rhythm of evergreen tropical trees was similarly related to precipitation patterns and that negative increments towards the end of the dry season were caused by stem shrinkage.

There was a marked reduction (>50%) in diameter increment in all treatments during the fifth year of growth. Plantation species that exhibit very high early growth rates, such as *E. grandis* in a tropical environment in Brazil established at the same stocking as used in this study, have been observed previously to then exhibit an equally rapid decline in growth rate as early as age 3 yr which is not associated with factors that determine growth rate; the precise reasons for such a decline remain unclear (Almeida et al. 2007). That the percentage decline was similar across all treatments suggests that this effect was apparently independent of stocking. However, a contributory factor to this decline may relate to the extended dry season in 2015 (total annual rainfall between December and April inclusive during course of the study was 213 mm, 301 mm and 127 mm), because of low incident rainfall in April (Figure 5.1), the band dendrometers indicating that resumption of diameter growth was approximately one month later than in previous years.

At age 5 yr, two or 3 yr after thinning, standing volumes were less in the thinned treatments than unthinned treatment. The effect of thinning time and intensity on stand volume development varies with species and growth rate (Kerr 1996, Kanninen et al. 2004, Kamo et al. 2009). Medhurst et al. (2001) recommended that their selection and the final stand density should be such that the growth rate of individual trees during the rotation should be maximised without seriously underutilizing site resources. The thinning practices tested in this study should be suitable for *Acacia* hybrid plantations as the trees respond quickly; if the final stand density is 600 ha^{-1}, the diameter of the remaining trees is >15 cm at age 5 yr, a size considered suitable for small sawlogs in Vietnam (Beadle et al. 2013). However, these larger logs should command a price premium so that the reduced harvested volume is more than offset by higher value.

5.4.2. Factors underpinning thinning response

In the three months after the early thinning and during the second half of the wet season, the thinned treatments developed *ca*. 0.5-0.6 unit of LAI and subsequently there was no difference in LAI between the un-thinned and 833 trees ha^{-1} treatment. Thus, levels of intra-specific competition for light in the 833 trees ha^{-1} treatment very quickly returned to those being experienced in the unthinned treatment; interestingly canopy recovery following late thinning to 833 trees ha^{-1} was slower, perhaps also reflecting the same reduction in vigour as was observed for the diameter response. In contrast, the LAI of the 600 tree ha^{-1} treatment remained lower for at least 12 months after thinning, although this difference was not always significant. Recovery of LAI in more heavily thinned treatments is linked to the continued growth of branches in the lower crown zone in response increased light availability (Medhurst and Beadle 2001), and this was confirmed by the development of a significantly greater crown length in the 600 tree ha^{-1} treatment. There was also a reduction in litterfall following both early- and late-thinning in the 600 tree ha^{-1} treatment, though only at the end of the wet and beginning of the dry season, and this appeared to be linked to a slower reduction of LAI in this treatment as the dry season developed; the slower recovery of LAI in the late-thinning 833 trees ha^{-1} treatment was also associated with a reduction in litterfall at this time. Decreases in litterfall with thinning intensity have been shown to result in a significant relationship between annual litterfall and basal area in *Acacia mangium* plantations (Kunhamu et al. 2009). That differences in LAI between treatments were small one year after thinning, and after late-thinning not significant, also suggests that thinning of *Acacia* hybrid to 600 trees ha^{-1} not only results in rapid crown development to maximise light interception, but following canopy closure, individual trees can still take advantage of the reduced competition for water and nutrients and sustain greater diameter growth than in unthinned or lightly thinned stands.

Following the early- and late-thinning, mean daily A_{1500} was greater in the lower crown zone of the 600 trees ha^{-1} treatments than unthinned treatment, and this difference was sustained for at least one year after the early thinning. Thus the higher diameter increments in this thinned treatment was driven at least in part by increased photosynthetic rates at the leaf level as well as retention of the lower crown. This result also confirms that a reduction in competition for light makes an important contribution to the thinning response and that this was probably less for 833 trees ha^{-1} treatment because of the more rapid crown closure. A similar study with *E. nitens* showed that significant increases in A_{1500} following thinning occurred in both the lower and middle crowns and primarily in the mature and old foliage (Medhurst and Beadle 2005). Thus as in their study, the shaded foliage of *Acacia* hybrid before thinning has a similar capacity to adapt to the marked increase in incident light, and for this species just a few weeks after thinning.

Medhurst and Beadle (2005) also found that improved A_{1500} after thinning of *E. nitens* was correlated with leaf N content, a finding that was related to lower SLA in the thinned than unthinned treatment. For *Acacia* hybrid, there were no treatment differences between these variables or N concentration; similarly, Yao et al. (2014) found no response of SLA to the thinning to *Eucalyptus dunnii* and *Corymbia citriodora* three years after thinning. In contrast, there was some indication that foliar P concentration and content were significantly greater in the 600 trees ha^{-1} treatment than the unthinned treatment, though only after the early thinning; and this was associated with reductions in P concentration being associated with lower A_{1500}. However, these differences may also be related to the relative dilution of the available P because of the greater LAI of the unthinned treatment (Messina 1992) as well as reduced competition for P favouring greater uptake in the 600 trees ha^{-1} treatment. The reduced foliar P concentration in both treatments following late thinning may be linked to the declining availability of soil P over a rotation (Huong et al 2015). Interestingly, the thinned trees had an increased δ^{15}N isotope ratio compared to the unthinned trees, suggesting that trees in thinned treatments had greater proportion of N derived from the atmosphere. Plantation *A. mangium* has been reported to fix up to 65.8 kg N ha^{-1} in pure acacia plantations during 30 months after planting (Bouillet et al. 2008). Thus, significantly more N-fixation following thinning may in some way also have underpinned the rapid canopy growth following thinning (Wibisono et al. 2015).

Light-saturated photosynthetic rate (A_{max}) was greater in T3 than T1 by 36.7 % in the lower crown four weeks after the early-age thinning and by 22.2 % six weeks after later-age thinning. This confirms that the rapid adaptation of *A.* hybrid to thinning is associated with increased photosynthetic capacity and this response conforms to the view that this species is not shade-tolerant (Kha 2001), hence the rapid response to increased light when canopy gaps are created, and the strong relationship between light environment and photosynthetic rate (Gauthier and Jacobs 2009). The significant time effect that resulted in lower mean photosynthetic rates, though only in the lower crown, in 2013 than 2012 may be related to a reduction in vigour with stand age which in *Eucalyptus saligna* was associated with a decline in LAI and photosynthetic capacity (Ryan et al. 2004). However, there no changes in light-use efficiency (Φ) with stand age or thinning treatment. Dark respiration (R_{dark}) was 62 % in greater in T3 than T1, most likely acclimation to the higher incident environment following thinning. The higher R_{dark} may potentially be related to the higher growth rates observed for T3 trees (Poorter et al. 1991).

Measurements of Ψ_{pd} indicated that trees were unable to rehydrate fully by the end of the dry season. In another study in Vietnam and Indonesia, stands of *Acacia* hybrid, *A. mangium and Acacia crassicarpa* aged around 1 yr also showed little recovery in Ψ_{leaf} at the end of the dry season (Eyles et al. 2015), and had similar Ψ_{pd}, around 1.0 MPa, at that time. However, in the current study at age 2.5 yr, minimum diurnal Ψ_{leaf} was -1.6 MPa whilst for *Acacia* hybrid, Eyles et al. (2015) found that the lowest value was -2.3 MPa). This difference may be because the younger trees still had root systems that were still not able to fully exploit the soil water store (Whitehead and Beadle 2004).

Thinning was associated with significantly higher levels of Ψ_{leaf} in both the wet and dry seasons. Pre-dawn water potential, Ψ_{pd} in a thinned *Quercus petraea* (Matt.) Liebl. stand was also found to be significantly greater than in an unthinned stand and this was attributed to higher relative extractable soil water as well as being associated with enhanced water-use efficiency (Breda et al. 1995). Thinned treatments have also been shown to conserve water for longer into the rotation in *Eucalyptus globulus* plantations in Western Australia (Mendham et al. 2011), as well as reducing the level of water stress experienced to the extent that thinning to 600 trees ha^{-1} had no significant effect on end-of-rotation stand volume compared to unthinned stands (White et al. 2009). Three years after thinning *Acacia* hybrid to 600 trees ha^{-1} in this study, stand volume was still significantly less than the control, but these results suggest that the reduced levels of water stress were partly responsible for the rapid recovery from thinning.

The strong linear relationship between rainfall for the previous three months and measured values of Ψ_{pd} and Ψ_{md} showed that the severity of water stress was also correlated to rainfall inputs. Similarly, Myers (1988) reported that Ψ_{leaf} of *Pinus radiata* D. Don plantation trees decreased rapidly from -0.5 MPa to -1.8 MPa during a summer drought event which only 88 mm of rainfall occurred from December to March. The soil water deficit was closely correlated to Ψ_{leaf} during this event (Myers 1988). Clearly, some production systems, including the rapidly growing *Acacia* hybrid plantations of the current study, affectively exploit soil so that there is minimal buffering from soil storage and tight coupling of tree water status to rainfall inputs.

5.4.3. Effects of season on tree growth and physiological characteristics

There are two main seasons in South Vietnam; the wet season from May to October and dry season is typically from November to April. Tree growth and physiological responses were substantially influenced by season in our study. Litterfall rates peaked in the middle of the dry season in January and February, which also corresponded to the time with the lowest leaf water potential (Ψ_{leaf}) of around -1.7 Mpa. These conditions led to a diameter increment at this time that was close to zero. Photosynthetic rates of *Acacia* hybrid trees were also affected by season, with photosynthetic rates at least three-fold higher in the wet (A_{1500} = 32.7 ± 1.4 μmol m^{-2} s^{-1}, measured at aged ten months) than the dry season (A_{1500} = 11.4 ± 2.3 μmol m^{-2} s^{-1}, measured at aged seven months (Eyles et al. 2015). Furthermore, Butt et al. (2014) reported that tree growth rates of six contrasting broadleaf temperate species significantly responded to spring temperature and precipitation. In our experiment, temperature was relatively stable throughout the year, therefore water and/or nutrient availability were the key seasonal factors influencing growth rates of *Acacia* hybrid plantations.

5.5. Conclusion

Elevated photosynthesis of the lower crown, associated with elevated foliar P, and reduced water stress during the dry season coupled with rapidly recovery of LAI led to significant diameter growth in *Acacia* hybrid plantation that had been thinned at both age two and age three. The early and more intensive thinning led to diameter gains of 16.7 %, but resulted in a 15.8 % decrease in stand volume. We estimate that the price premium for the larger logs that would be required to offset the volume loss would be around $ 55 US m^{-3}. Alternatively, the moderate thinning regime resulted in marginally larger trees (average of 7.5% greater diameter), but no significant loss in stand volume. There were no significant differences in diameter between earlier moderate and later moderate thinning treatments (800 trees ha^{-1}), but there was significantly lower standing volume in more intensive thinning (to 600 trees ha^{-1}), both for the early- and later-age thinning treatments. From our results, earlier intensive thinning or later moderate thinning are likely to convey greater benefit to acacia growers, but the investment decision to undertake a thinning operation should account for the projected market value of different log sizes and the risks associated with longer rotations.

Chapter 6. Summary and implications for management

This study has investigated the physiological and growth responses of tropical acacia plantations (*Acacia auriculiformis* and *Acacia* hybrid) to arrange of management actions; specifically slash retention, thinning and phosphorus fertiliser application. This information is important to improve productivity and sustainability; and to achieve optimal sawlog values from plantation areas that have traditionally been established for pulp production. A literature review highlighted the role of resource constraints in affecting the productivity of plantations. Managing resource constraints such as the availability of nutrients, water and light, can be implemented through changing planation management practices. This study examined tree growth and physiological bases for the responses to slash and fertiliser management and thinning at different stages of stand development. I tested the hypothesis that constraints in nutrients and/or water and light resources are the basis for these responses. The rationale for focusing on potential resource constraints is that they offer opportunity for management intervention. This chapter summarises the key findings and conclusions, and the implications for management. Recommendations for future research to increase productivity and quality of acacia plantations in Vietnam are discussed.

6.1. Key findings

A review of the literature (Chapter 2) highlighted the following key learnings:

- The inter-rotation phase is crucial for the conservation of soil structure and function in order to maintain and improve the productivity and sustainability of plantations.

- A variety of practices including fertilisation, legume intercropping, slash and litter retention and well managed site preparation practices (e.g. no burning of harvest residues, slashing and herbicide application instead of bulldozing) were identified.
- In particular, the retention of slash and litter after harvesting offered potential for maintaining soil organic carbon and nutrients.

While most of the published studies into slash management have focused on eucalypt plantations, there are only a few published studies in acacia plantations, and none that report on the effect of repeated slash manipulation treatments over two consecutive rotations. Consequently, the experiment described in Chapter 3 was designed to understand the potential role of slash and litter for managing productivity over several rotations of acacia plantations.

Improving productivity and sustainability of successive rotations of Acacia auriculiformis plantations in South Vietnam (Chapter 3).

- Removal of slash and litter after harvesting a low yielding first rotation crop at age 7 yr reduced the standing volume of the second rotation by 13% compared to treatments with slash and litter retained.
- Slash and litter retention reduced the soil bulk density and increased soil organic carbon content by 26% and nitrogen by 40% in the 0 - 10 cm soil layer compared to levels at the start of the second rotation.

• Extractable soil P declined during the second rotation, but there was no growth response to P fertiliser at that time. However, there was a response to P fertiliser in the third rotation.

Slash retention had positive impacts on soil structure and improved the soil fertility. In addition, combining slash retention and phosphorus fertiliser application in the third rotation (age five years) led to an increased stand volume of 18.1 % compared to the treatments with slash and litter removed.

A further key management option for optimising resource capture into high value product is the practice of thinning to improve access of the remaining trees to light, water and soil nutrients. However, the effects of mid-rotation thinning (age ~4 yr), slash retention and application of phosphorus fertiliser on the growth and physiological response of *A. auriculiformis* plantations were previously unknown. Therefore, Chapter 4 describes a study that examined the effects of thinning and the interactions with slash retention and P fertiliser management on tree growth and physiological responses.

Growth and physiological response of A. auriculiformis plantations to mid-rotation thinning, application of phosphorus fertiliser and organic matter retention in South Vietnam (Chapter 4).

• Thinning to 833 trees ha^{-1} from an initial planted density of 1667 trees ha^{-1} of *Acacia auriculiformis* at age four years significantly increased foliar photosynthetic rate (Amax), relative to unthinned trees, one year after thinning.

- Thinning increased foliar N and P concentrations one and two years after thinning, respectively.

- Leaf area index (LAI) in thinned treatments remained lower than in unthinned treatments during the course of the study.

- The only significant differences in litterfall between thinned and unthinned treatments were detected nine months after thinning in the driest months (January, February 2014 and January 2015). Thinned treatments had less litterfall than unthinned.

- By age seven years, the average stem diameter in thinned treatments was significantly higher than in unthinned treatments. Therefore, recovery of larger size-class logs was significantly higher in thinned than in unthinned treatments.

- Gross stand value of wood products up to age seven years was higher in the thinned treatments (including the thinning harvested in year 4) compared to the unthinned treatments.

- The thinning treatment, when also combined with addition of 50 kg P ha^{-1}, increased foliar A_{max}, but P fertiliser application did not increase foliar A_{max} in the unthinned treatment.

- Phosphorus fertiliser application increased the rate of canopy development in thinned treatments so that there was no significant difference in LAI between thinned plus P fertiliser and unthinned treatments beyond 20 months after thinning.

- Removal of slash and litter at thinning time was correlated with a trend (non-significant) in decreased tree growth rate.

The results from the study described in Chapter 4 highlighted that thinning and P fertiliser application were able to ameliorate nutrient constraints. However, increased litterfall in the unthinned treatments indicated that water availability could be a key constraint to growth rate in the absence of significant constraints in soil fertility. To explore this further, the study described in Chapter 5 examined the effects of thinning intensity and timing on water relations of *Acacia* hybrid plantations.

Growth and physiological responses to intensity and timing of thinning in short rotation tropical Acacia hybrid plantations in South Vietnam (Chapter 5).

- Leaf area index in trees thinned at age 2 yr recovered rapidly and there was no significant difference in LAI between unthinned and thinned treatments by one year after thinning.

- Intensive thinning increased photosynthetic rates of the lower crown by 30% five weeks after thinning at age two years. This was also associated with a 38% increase in foliar P concentration. In contrast, there were no significant differences in photosynthetic rates or foliar P concentration after thinning at age three years.

- Thinning reduced leaf water stress by 16.4 % during the dry season as estimated by measurement of leaf water potential.

- Early and more intensive thinning (to 600 stems/ha at age 2 yr) led to diameter gains of around 2.3 cm, representing a 16.7 % increase over the control unthinned treatment, but this was also associated with a 15.8 % decrease in stand volume. The moderate thinning regime also resulted in significantly larger trees (average of 7.5% greater diameter), but there was no significant loss in stand volume. There were no significant differences in tree diameter at age 5 yr between the earlier and later moderate thinning treatments (800 trees ha^{-1}), but there was significantly lower standing volume in more intensive thinning (to 600 trees ha^{-1}), both for the early- and later-age thinning treatments.

The results of this chapter indicate that water availability during the dry season is a key constraint to tree growth that can be ameliorated to some extent by adopting an appropriate thinning practice.

6.2. Implications for future best practice management

The following recommendations are based on integrating the findings from this study and current best practice:

6.2.1. Maintenance of productivity and optimising stand management

Current silvicultural practices of acacia plantations in Vietnam typically include clear-fall cutting of the plantations at harvest, burning slash and litter after harvesting, using a bulldozer for land preparation and repeated ploughing and the burning of litter every year for weed control. These practices can be destructive, and can cause losses of soil organic matter, soil organisms and soil function that lead to decreased productivity of plantations over multiple rotations. Findings reported in Chapter 3 indicate that slash and litter retention can increase substantially soil organic carbon and nitrogen, and reduce the depletion of soil available P in the third rotation. Thus, it is possible and necessary to implement a suite of integrated management practices to conserve and maintain organic matter and nutrients that will ensure the sustainability of fast-growing acacia plantations in the tropics.

Site preparation and pre-planting herbicide application:

Site preparation aims to improve the survival rate of trees and to promote early uniform and fast tree growth. Currently, site preparation techniques include bulldozing and the burning of slash and litter to kill seed and coppice shoots of weeds. However, this method can accelerate soil erosion (especially on steep sites) and damage soil structure and function. Consequently, minimum cultivation including slash and litter retention at the site after harvesting, and soil preparation in planting rows or pits (Gonçalves et al. 2008a), is recommended.

Pre-planting herbicide application is critical. Applying 4 L ha^{-1} of Round-up 480SCcontaining 0.48 g L^{-1} and 1.92 kg ha^{-1} *Glyphosate isopropylamine* salt around one month after slashing weeds and bamboo species is the best practice, rather than manual weeding or cultivation.

Application of these practices was a key factor in the site and stand management of the experiments in this study, leading to high (relative to current industry practice) survival and growth rates.

Fertilisers at planting:

Fertiliser applications are commonly used in commercial acacia plantations in Vietnam due to a response of increased growth and crown development during the first 3 yr (Bon and Harwood 2014) or 4 years (Huong et al. 2008) after planting. However, high rates of fertiliser application, equivalent to 50 kg of elemental phosphorus (P) per hectare at planting (Beadle et al. 2013), led to excessive branch growth and consequent breakage of 20% compared to 6.1% in the no P fertiliser control (Bon and Harwood 2014). Therefore, we recommend that the application rate be revised between to10 and 20 kg elemental P per hectare, applied as superphosphate (Huong et al. 2008; Mendham 2010; Bon and Harwood 2014, Harwood et al. 2014).

Post planting weed control:

Applying herbicide in strips 1.5 wide along tree rows significantly increased the volume of *Acacia auriculiformis* plantations (Huong et al. 2008). Herbicides should be applied during the first three years in commercial acacia plantations. Current recommended best practice is manual slashing at three months before herbicide application at six months. In years 2 and 3, herbicide should be applied before and after the wet season.

Thinning:

Acacia hybrid is now the most planted species in Vietnam for pulpwood production with a high density of initial planting (> 1666 trees ha^{-1}). Plantations are often established using unsuitable planting stock. Therefore, applying thinning to ensure the production of high-quality sawlogs without loss of volume at the end of the rotation is an ideal objective. However, *Acacia* hybrid is susceptible to branch damage from high wind events (Beadle et al. 2013), so thinning should be not applied to *A*. hybrid plantations where sites are exposed to high winds. In contrast, *A. auriculiformis* may be a more suitable species for sawlog production because of inherently smaller branches which are less susceptible to breakage. Mid-rotation thinning can be applied to *A. auriculiformis* plantations whilst maintaining half the initial stocking (Chapter 4). Thinning also should be undertaken to remove from 25 to 45 % of the initial planting density of *Acacia* hybrid plantations for late and early thinning, respectively (Chapter 5). *A. auriculiformis* also appears to be more resistant to disease than *Acacia* hybrid, so may be more suitable in the longer term.

There are several methods of applying thinning regimes, but the main approaches are: system thinning (systematic, mechanical, line thinning); selective thinning (low thinning, crown thinning); thinning selection and; Queensland selection system (Evans and Turnbull 2004, West 2014). However, an alternative practice of low crown thinning and selection thinning, that has resulted in anecdotally superior growth rates and form, is recommended. This practice should be undertaken on a row-by-row basis and trees selected for thinning will be based on the criteria of poor form, damage and small diameter.

Fertiliser application at thinning:

Thinning and fertiliser are often applied simultaneously in commercial plantations. Phosphorus (P) and basal fertiliser have been applied at thinning of Acacia hybrid plantations (Beadle et al. 2013). Tree growth response to P and basal fertiliser at thinning was observed at sites with low soil fertility, but not at sites where 50 kg P ha^{-1} was applied at planting, which appeared to result in the P status of the plants being adequately met through the rotation. In addition, applying 50 kg P ha^{-1} at thinning of 4-yr *A. auriculiformis* plantations did not significantly improved tree growth rate (Chapter 4). Thus, site quality should be assessed before simultaneously applying thinning and fertiliser in acacia plantations.

6.2.2. Future research

Acacia growers may receive the best outcomes of optimal productivity with low associated risk by improved management of plantations for both saw-log and pulpwood production. Future research opportunities toward this outcome include the following:

- Theme 1: Huong et al. (2015) have demonstrated the importance of adopting conservative management practices to ensure sustainable production over multiple rotations, and developed a wealth of information on the impact of these management practices on soil, organic matter and nutrient resources. Given the very large areas of acacia plantations in Vietnam, and the importance of maintaining production levels into the future, to ensure that farmers and processors continue to receive the benefits from these plantations, continuation of this unique study is warranted.

- Theme 2: in Vietnam, sites for acacia plantation forests with short rotations of 6 - 8 yr are often located on steep slopes. Methods of clear-fell harvesting and slash burning for land preparation are commonly applied causing negative impacts on site, soil fertility and sustainable wood production. Therefore, future studies need to provide a better understanding of how to integrate best-practice inter-rotation practices (e.g. retaining slash and litter at site after harvesting) to avoid soil damage, reduce soil erosion and conserve site resources on steep sites.

- Theme 3: Understanding the benefits of slash retention on soil organic matter and plantation productivity, and separating the contributions of the organic matter and nutrients in the slash, so that better recommendations can be made about the ability to remove slash, and substitute the nutrients with fertilser.

- Theme 4: Better understanding the responses of acacias to less intensive and later (commercial) thinning, to align with farmer expectations of high incomes and taking low risk in commercial plantations. What is the capacity of the system to undertake more commercial thinnings later in the rotation, perhaps applying multiple thinnings, or even on an annual basis?

- Theme 5: Better understanding of the economics of saw-log rotations vs pulpwood (including longer-term monitoring of existing experiments), so that we can be clearer in our recommendations to farmers about their best options

- Theme 6: Targeting of species to products. *A.* hybrid has problems currently for sawlog production because of its susceptibility to wind-throw and disease. What options are there to improve this – are there more suitable hybrid lines, or is a species change to (eg. *A. auriculiformis*) the best option?

- Theme 7: The possibility exists that acacias in Vietnam may succumb to widespread disease which would be devastating to the industry (as has happen in Sumatra), so alternative species such as eucalypts need to be better understood so that they can be rapidly deployed in the event that this becomes necessary. This includes better understanding the impacts of acacias on the site, and the implications for management of a following non-N-fixing species rotation.

6.3. Overall conclusion

The research contained in this thesis has filled some knowledge gaps in the current management of pulpwood *Acacia* plantations in Vietnam. It has reviewed, identified and researched potential management options to improve the sustainability of production and the quality, yield and value of current pulpwood plantations by facilitating the production of saw-logs. The research has led to revised management recommendations to improve the productivity and sustainability of timber production from *Acacia* plantations. Areas of further research have been identified to support long-term timber production in Vietnam.

References

Abramoff MD, Magalhães PJ, Ram SJ (2004) Image Processing with ImageJ. Biophotonics 11:36-42.

Adams MA, Simon J, Pfautsch S (2010) Woody legumes: a (re)view from the South. Tree Physiolpgy 30:1072-1082.

AGROINFOR (2014) Annual report 2013 of wood sector and prospect for 2014. Ha Noi: Information Center for Agriculture and Rural Development (AGROINFOR)

Almeida AC, Soares JV, Landsberg JJ, Rezende GD (2007) Growth and water balance of *Eucalyptus grandis* hybrid plantations in Brazil during a rotation for pulp production. Forest Ecology and Management 251:10-21.

Armstrong DL, Griffin KP (1999) Phosphorus for agriculture. Better crops 83:4-39.

Attiwill PM, Adams MA (1993) Tansley Review No. 50. Nutrient Cycling in Forests. New Phytologist 124:561-582.

Attiwill PM, Leeper GW (ed) (1987) Forest soils and nutrient cycles.

Battaglia M, Beadle C, Loughhead S (1996) Photosynthetic temperature responses of *Eucalyptus globulus* and *Eucalyptus nitens*. Tree Physiology 16:81-89.

Battaglia M, Cherry ML, Beadle CL, Sands PJ, Hingston A (1998) Prediction of leaf area index in eucalypt plantations: effects of water stress and temperature. Tree Physiology 18:521-528.

Beadle C, Dung PT, Cao TT, Dat KT, Bon PV, Quang LT, Harwood C (2015) Extending silvicultural knowledge on sawlog production from *Acacia* plantations: Final Report, ACIAR Project FST/2014/017. Australian Centre for International

Agriculture Research, ACIAR, GPO Box 1571, Canberra ACT 2601, Australia, p 61.

Beadle C, Trieu DT, Harwood CE (2013) Thinning increased saw-log values in fast growing plantations of *Acacia* hybrid in Vietnam. Journal of Tropical Forest Science 25:42-51.

Beadle CL (1997) Dynamic of leaf and canopy development. In: Nambiar EKS, Brown AG (eds) Management of Soil, Nutrients and Water in Tropical Plantation Forests. Australian Centre for International Agricultutal Research (ACIAR), Canberra, Australia, pp 169-212.

Beadle CL, Talbot H, Jarvis PG (1982) Canopy Structure and Leaf-Area Index in a Mature Scots Pine Forest. Forestry 55:105-123.

Bernhard-Reversat F (1996) Nitrogen cycling in tree plantations grown on a poor sandy savanna soil in Congo. Applied Soil Ecology 4:161-172.

Bin H, Wuming Q, Jun D, Qingbiao W, Feng L, Yong H (2007) Function and value of water conservation in different age classes of *Acacia mangium* plantations. Forontiers of Forestry in China 2:443-447.

Binkley D (2005) How Nitrogen-Fixing Trees Change Soil Carbon. In: Binkley D, Menyailo O (eds) Tree Species Effects on Soils: Implications for Global Change. Springer Netherlands, pp 155-164.

Binkley D, Giardina C (1997) Nitrogen fixation in tropical forest plantations. In: Nambiar EKS, Brown AG (eds) Management of Soil, Nutrients and Water in Tropical Plantation Forests. Australian Centre for International Agricultutal Research (ACIAR), Canberra, pp 297-337.

Binkley D, Kaye J, Barry M, Ryan MG (2004) First-rotation changes in soil carbon and nitrogen in a Eucalyptus plantation in Hawaii. Soil Science Society of America Journal 68:1713-1719.

Binkley D, O'Connell AM, Sankaran KV (1997) Stand Development and Productivity. In: Nambiar EKS, Brown AG (eds) Management of Soil, Nutrients and Water in Tropical Plantation Forests. Australian Centre for International Agricultutal Research (ACIAR), Canberra, pp 419-442.

Blyth MJ, Hoang LS (2013) Socio-economic factors influencing smallholder production of acacia sawlogs in Vietnam: Final Report ACIAR Project FST/2007/025. Australian Centre for International Agricultural Research, ACIAR, GPO Box 1571, Canberra ACT 2601, Australia.

Bon PV, Harwood CE (2014) Effects of hedge plant age and fertilizer on growth and form of three *Acacia* hybrid clones. In: Griffin AR (Ed.), Acacia 2014 "Sustaining the Future of Acacia Plantation Forestry". International Conference. Working Party 1.08.07: Genitics and Silviculture of Acacia. Hue - Vietnam, p. 107.

Bouillet JP, Laclau JP, Gonçalves JLM, Moreira MZ, Trivelin PCO, Jourdan C, Silva EV, Piccolo MC, Tsai SM, Galiana A (2008) Mixed-species plantations of *Acacia mangium* and *Eucalyptus grandis* in Brazil: 2: Nitrogen accumulation in the stands and biological N2 fixation. Forest Ecology and Management 255:3918-3930.

Breda N, Granier A, Aussenac G (1995) Effects of thinning on soil and tree water relations, transpiration and growth in an oak forest (*Quercus petraea* (Matt.) Liebl.). Tree Physiology 15:295-306.

Bredenkamp BV (1984) The CCT concept in spacing research- a review. In: Grey DC, Schönau APG, Schutz CJ (Eds.), Symposium on Site and Productivity of Fast-Growing Plantations. Pretoria and Pietermaritzburg, South Africa, 30 April-11 May 1984. South African Forest Research Institute, pp. 313-332.

Brockley RP (2005) Effects of post-thinning density and repeated fertilization on the growth and development of young lodgepole pine. Can J Forest Res 35:1952-1964.

Butt N, Bebber DP, Riutta T, Crockatt M, Morecroft MD, Malhi Y (2014) Relationships between tree growth and weather extremes: Spatial and interspecific comparisons in a temperate broadleaf forest. Forest Ecology and Management 334:209-216.

Cassidy M, Palmer G, Glencross K, Nichols JD, Smith RGB (2012) Stocking and intensity of thinning affect log size and value in *Eucalyptus pilularis*. Forest Ecology and Management 264:220-227.

Cienciala E, Kucera J, Malmer A (2000) Tree sap flow and stand transpiration of two *Acacia mangium* plantations in Sabah, Borneo. J Hydrol 236:109-120.

Close D (2012) A review of ecophysiologically-based seedling specifications for temperate Australian eucalypt plantations. New Forest 43:739-753.

Comfort EJ, Roberts SD, Harrington CA (2010) Midcanopy growth following thinning in young-growth conifer forests on the Olympic Peninsula western Washington. Forest Ecology and Management 259:1606-1614.

Coplen TB (1988) Normalization of oxygen and hydrogen isotope data. Chemical Geology: Isotope Geoscience Section 72:293-297.

Craswell ET, Lefroy RDB (2001) The role and function of organic matter in tropical soils. Nutrient Cycling in Agroecosystems 61:7-18.

Davi H, Baret F, Huc R, Dufrêne E (2008) Effect of thinning on LAI variance in heterogeneous forests. Forest Ecology and Management 256:890-899.

David P (2002) Twenty-year results of precommercial thinning in a balsam fir stand. Forest Ecology and Management 168:177-186.

Deadman H, Hay A (1987) Eucalypts-selecting high quality tree crops. What's new in forest research Forest Research Institute, Rotorua, New Zealand

Dias LE, Franco AA, Campello EFC (1994) Organic matter and nutrient dynamics in bauxite mined soil cultivated with *Eucalyptus pellita* and *Acacia mangium*. In: Balensiefer M, de Araújo AJ, Rosot NC (Eds.), Simpósio Sul-americano I e Simpósio National II de Recupercdo de Áreas Degradadas. Curitiba. Fundacão de Pesquisas Florestais do Paraná, pp. 515-526.

Dong TL, Doyle R, Beadle CL, Corkrey R, Quat NX (2014) Impact of short-rotation Acacia hybrid plantations on soil properties of degraded lands in Central Vietnam. Soil Research 52:271.

Drake PL, Mendham DS, White DA, Ogden GN (2009) A comparison of growth, photosynthetic capacity and water stress in *Eucalyptus globulus* coppice regrowth and seedlings during early development. Tree Physiol 29:663-674.

du Toit B (2003) Effects of site management operations on the nutrient capital of a eucalypt plantation system in South Africa. Southern African Forestry Journal:15-25.

du Toit B, Dovey SB, Smith CW (2008) Effects of slash and site management treatments on soil properties, nutrition and growth of a *Eucalyptus grandis* plantation in South Africa. In: Nambiar EKS (Ed.), Site management and productivity in tropical plantation forests. Proceedings of Workshops in Piracicaba (Bazil) 22-26 November 2004 and Bogor (Indonesia) 6 - 9 November 2006. Center for International Forest Research (CIFOR), pp. 63-78.

Dung PT, Ngoc NV, Phuc HV, Le NT, Thuan NT, Tung PV, Binh NT (2005) Techniques for the intensive establishment of selected clones of *Acacia* hybrid on old alluvial soil in Binh Phuoc province for pulpwood. In:0 Project Report. Forest Science Institute of Vietnam, Ha Noi, Vietnam.

Evans J, Turnbull JW (ed) (2004) Plantation Forestry in the Tropics: The role, silviculture and use of planted forests for industrial, social, environmental and agroforestry purposes. Oxford University Press, UK.

Eyles A, Drake P, Quang LT, Van Bon P, Mendham D, White D, Dat KT, The Dung P, Beadle C (2015) Ecophysiology of Acaciaspecies in wet–dry tropical plantations. Southern Forests: a Journal of Forest Science:1-10.

Eyles A, Smith D, Pinkard EA, Smith I, Corkrey R, Elms S, Beadle C, Mohammed C (2011) Photosynthetic responses of field-grown *Pinus radiata* trees to artificial and aphid-induced defoliation. Tree Physiology 31:592-603.

Flinn DW, Squire RO, Farrell FW (1980) The role of organic matter in the maintenance of site productivity on sandy soils. New Zealand Journal of Forestry 25:229-236.

Folster H, Khanna PK (1997) Dynamics of Nutrient Supply in Plantation Soils. In: Nambiar EKS, Brown AG (eds) Management of Soil, Nutrients and Water in Tropical Plantation Forests. Australian Centre for International Agricultutal Research (ACIAR), Canberra, pp 339-378.

Forest Science Institute of Vietnam Nguyen Hoang Nghia, Nguyen Xuan Quat, Dang Van Thuyet (ed) (2010) Plantation Technique of some species for sawlog. Agricultural House, Ha Noi.

Forrester DI (2013) Growth responses to thinning, pruning and fertiliser application in *Eucalyptus* plantations: A review of their production ecology and interactions. Forest Ecology and Management 310:336-347.

Forrester DI, Baker TG (2012) Growth responses to thinning and pruning in *Eucalyptus globulus*, *Eucalyptus nitens*, and *Eucalyptus grandis* plantations in southeastern Australia. Can J Forest Res 42:75-87.

Forrester DI, Collopy JJ, Beadle CL, Baker TG (2012a) Interactive effects of simultaneously applied thinning, pruning and fertiliser application treatments on growth, biomass production and crown architecture in a young *Eucalyptus nitens* plantation. Forest Ecology and Management 267:104-116.

Forrester DI, Collopy JJ, Beadle CL, Baker TG (2013) Effect of thinning, pruning and nitrogen fertiliser application on light interception and light-use efficiency in a young *Eucalyptus nitens* plantation. Forest Ecology and Management 288:21-30.

Forrester DI, Collopy JJ, Beadle CL, Warren CR, Baker TG (2012b) Effect of thinning, pruning and nitrogen fertiliser application on transpiration, photosynthesis and water-use efficiency in a young *Eucalyptus nitens* plantation. Forest Ecology and Management 266:286-300.

Forrester DI, Medhurst JL, Wood M, Beadle CL, Valencia JC (2010) Growth and physiological responses to silviculture for producing solid-wood products from *Eucalyptus* plantations: An Australian perspective. Forest Ecology and Management 259:1819-1835.

Galloway G, Ugalde L, Vasquez W (2001) Importance of density reductions in tropical plantations: Experiences in Central America. Forests Trees and Livelihoods 11:217-232.

Garay I, Pellens R, Kindel A, Barros E, Franco AA (2004) Evaluation of soil conditions in fast-growing plantations of *Eucalyptus grandis* and *Acacia mangium* in Brazil: a contribution to the study of sustainable land use. Applied Soil Ecology 27:177-187.

Gauthier M-M, Jacobs DF (2009) Short-Term Physiological Responses of Black Walnut (*Juglans nigra* L.) to Plantation Thinning. Forest Science 55:221-229.

Glencross K, Nichols JD, Grant JC, Sethy M, Smith RGB (2012) Spacing affects stem form, early growth and branching in young whitewood (*Endospermum medullosum*) plantations in Vanuatu. International Forest Review 14:442-451.

Gonçalves JLM, Alvares CA, Higa AR, Silva LD, Alfenas AC, Stahl J, Ferraz SFD, Lima WDP, Brancalion PHS, Hubner A, Bouillet JPD, Laclau JP, Nouvellon Y, Epron D (2013) Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian eucalypt plantations. Forest Ecology and Management 301:6-27.

Gonçalves JLM, Barros NF, Nambiar EKS, Novais RF (1997) Soil and Stand Management for Short-rotation Plantations. In: Nambiar EKS, Brown AG (eds) Management of Soil, Nutrients and Water in Tropical Plantation Forests. Australien Centre for International Agricultutal Research (ACIAR); CSIRO Australia; CIFOR Indonesia, pp 379-417.

Gonçalves JLM, Poggiani F, Stape JL, Serrano MIP, Mello SLDM, Mendes KCFS, Gava JL, Benedetti V (1999) Eucalypt plantations in the humid tropics: Sao Paulo, Brazil. In: Nambiar EKS, Cossalter C, Tiarks A (Eds.), Site Management and Productivity in Tropical Plantation Forests. Proceeding of Wrkshop in Pietermaritzburg 16-20 February 1998, South Africa Center for International Forestry Research (CIFOR), pp. 5-12.

Gonçalves JLM, Stape JL, Laclau JP, Bouillet JP, Ranger J (2008a) Assessing the effects of early silvicultural management on long-term site productivity of fast-growing eucalypt plantations: the Brazilian experience. South Forests 70:105-118.

Gonçalves JLM, Wichert MCP, Gava JL, Masetto AV, Junior JCA, Serrano MIP, Mello SLM (2007) Soil fertility and growth of *Eucalyptus grandis* in Brazil under different residue management practices. South Hemisph for J 69:95-102.

Gonçalves JLM, Wichert MCP, Gava JL, Serrano MIP (2008b) Soil Fertility and Growth of *Eucalyptus grandis* in Brazil under Different Residue Management Practices. In: Nambiar EKS (Ed.), Site management and productivity in tropical plantation forests. Proceedings of Workshops in Piracicaba (Bazil) 22-26 November 2004 and

Bogor (Indonesia) 6 - 9 November 2006. Center for International Forest Research (CIFOR), pp. 51-62.

Greenland DJ, Rimmer D, Payne D (1975) Determination of the structural stability class of English and Welsh soils, using a water coherence test. Journal of Soil Science 26:294-303.

Griffith B (2001) Efficient Fertilizer Use- Phosphorus. In: Efficient fertilizer use manual. Mosaic, p 8.

Guiterman CH, Seymour RS, Weiskittel AR (2012) Long-term thinning effects on the leaf area of *Pinus strobus* L. as estimated from litterfall and individual-tree allometric models

Hai PH, Harwood C, Kha LD, Pinyopusarek K, Thinh HH (2008) Genetic gain from breeding *Acacia auriculiformis* in Vietnam. Journal of Tropical Forest Science 20:313-327.

Hardiyanto EB, Nambiar EKS (2014) Productivity of successive rotations of *Acacia mangium* plantations in Sumatra, Indonesia: impacts of harvest and inter-rotation site management. New Forest 45:557-575.

Hardiyanto EB, Wicaksono A (2008) Inter-rotation site management, stand growth and soil properties in *Acacia mangium* plantations in South Sumatra, Indonesia. In: Nambiar EKS (Ed.), Site management and productivity in tropical plantation forests. Proceedings of Workshops in Piracicaba (Bazil) 22-26 November 2004 and Bogor (Indonesia) 6 - 9 November 2006. Center for International Forest Research (CIFOR), pp. 107 - 122.

Harwood CE, Nambiar EKS (2014) Productivity of acacia and eucalypt plantations in Southeast Asia. 2. trends and variations. Int Forest Rev 16:249-260.

Howard PJA, Howard DM (1990) Use of organic carbon and loss-on-ignition to estimate soil organic matter in different soil types and horizons. Biol Fert Soils 9:306-310.

Huong VD, Nambiar EKS, Quang LT, Mendham DS, Dung PT (2015) Improving productivity and sustainability of successive rotations of *Acacia auriculiformis* plantations in South Vietnam. Southern Forests: A Journal of Forest Science 77:51-58.

Huong VD, Quang LT, Binh NT, Dung PT (2008) Site management and productivity of *Acacia auriculiformis* plantations in South Vietnam. In: Nambiar EKS (Ed.), Site management and productivity in tropical plantation forests. Proceedings of Workshops in Piracicaba (Brazil) 22-26 November 2004 and Bogor (Indonesia) 6 - 9 November 2006. Center for International Forest Research (CIFOR), pp. 123-137.

Inagaki M, Kamo K, Yamada T, Titin J (2008) Soil water conditions according to landscape position and aboveground vegetation in an Acacia mangium plantation in Sabah, Malaysia. Jarq-Jpn Agr Res Q 42:69-76.

Jaakkola T, Mäkinen H, Saranpää P (2006) Wood density of Norway spruce: Responses to timing and intensity of first commercial thinning and fertilisation. Forest Ecology and Management 237:513-521.

Kamo K, Vacharangkura T, Tiyanon S, Viriyabuncha C, Thaingam R, Sakai M (2009) Response of unmanaged *Acacia mangium* plantations to delayed thinning in North-East Thailand. Journal of Tropical Forest Science 21:223-234.

Kanninen M, Pérez D, Montero M, Víquez E (2004) Intensity and timing of the first thinning of *Tectona grandis* plantations in Costa Rica: results of a thinning trial. Forest Ecology and Management 203:89-99.

Kay BD, Angers DA Sumner ME (ed) (1999) Soil Structure. CRC Press, Boca Raton.

Kellogg CE (1950) Soil: The loose material of the earth's surface is in constant process of evolution. Its variety deeply influences the life of man. Scientific America, INC:30-39.

Kerr G (1996) The effects of heavy or 'free growth' thinning on oak (*Quercus petraea* and *Q. robur*). Forestry 69 (4):303-317.

Kha LD (ed) (2001) Studies on the use of natural hybrids between *Acacia mangium* and *Acacia auriculiformis* in Vietnam. Agricultural Publishing House, Ha Noi.

Kha LD, Harwood CE, Kien ND, Baltunis BS, Hai ND, Thinh HH (2012) Growth and wood basic density of acacia hybrid clones at three locations in Vietnam. New Forest 43:13-29.

Kien ND, Thinh HH, Kha LD, Nghia NH, Hai PH, Hung TV (2014) Acacia as national resoures of Vietnam. In: Griffin AR (Ed.), Acacia 2014 "Sustaining the Future of Acacia Plantation Forestry". International Conference. Working Party 1.08.07: Genitics and Silviculture of Acacia. Hue - Vietnam, p. 20.

Körschens M, Weigel A, Schulz E (1998) Turnover of soil organic matter (SOM) and long-term balances - tools for evaluating sustainable productivity of soils. Zeitschrift für Pflanzenernährung und Bodenkunde 161:409-424.

Kozlowski TT, Pallardy SG (1997a) Environmental Regulation of Vegetative Growth. In: Kozlowski TT, Pallardy SG (eds) Growth Control in Woody Plants. Academic Press, San Diego, California 92101-4495, USA, pp 195-322.

Kozlowski TT, Pallardy SG (1997b) Physiological Regulation of Vegetative Growth. In: Kozlowski TT, Pallardy SG (eds) Growth Control in Woody Plants. Academic Press, Inc., San Diego, California 92101-4495, USA, pp 73-165.

Kozlowski TT, Pallardy SG (ed) (1997c) Physiology of Woody Plants. Academic Press, Inc., San Diego, California 9210-445, USA.

Krull ES, Skjemstad JO, Baldock JA (2004) Functions of soil organic matter and the effect on soil properties. In:0 Residue Management, Soil Organic Carbon and Crop Performance. GRDC and CSIRO Land & Water, p 129.

Kunhamu TK, Kumar BM, Viswanath S (2009) Does thinning affect litterfall, litter decomposition, and associated nutrient release in *Acacia mangium* stands of Kerala in peninsular India? Can J Forest Res 39:792-801.

Laclau JP, Levillain J, Deleporte P, Nzila JD, Bouillet JP, Saint Andre L, Versini A, Mareschal L, Nouvellon Y, M'Bou AT, Ranger J (2010) Organic residue mass at planting is an excellent predictor of tree growth in *Eucalyptus* plantations established on a sandy tropical soil. Forest Ecology and Management 260:2148-2159.

Landsberg J, Gower S (1997) Forest Hydrology and Tree–Water Relations. In: Gower JJLT (ed) Applications of Physiological Ecology to Forest Management. Academic Press, San Diego, pp 89-124.

Landsberg J, Sands P (ed) (2010a) Physiologycal Ecology of Forest Production: Principles, Processes and Models. Academic Press.

Landsberg JJ, Sands P (ed) (2010b) Physiological ecology of forest production: principles, processes and models. Academic Press.

Lowther LP (1980) Use of a single sulphuric acid-hydrogen peroxide digest for ananlysis of *Pinus radiata* needles. Commun Soil Sci Plan 11:175 - 188.

Lugo AE, Brown S, Chapman J (1988) An analytical review of production rates and stemwood biomass of tropical forest plantations. Forest Ecology and Management 23:179-200.

Macedo MO, Resende AS, Garcia PC, Boddey RM, Jantalia CP, Urquiaga S, Campello EFC, Franco AC (2008) Changes in soil C and N stocks and nutrient dynamics 13 years after recovery of degraded land using leguminous nitrogen-fixing trees. Forest Ecology and Management 255:1516-1524.

Mäkinen H, Isomäki A (2004) Thinning intensity and growth of Scots pine stands in Finland. Forest Ecology and Management 201:311-325.

MARD (2014) Approval for action strategy to improve productivity, quality and value of commercial plantations during period 2014 - 2020. So 774/QD-BNN-TCCN Ed. Ministry of Agriculture and Rural Development, Ha Noi- Vietnam, p 23.

Medhurst JL, Battaglia M, Beadle CL (2002) Measured and predicted changes in tree and stand water use following high-intensity thinning of an 8-year-old *Eucalyptus nitens* plantation. Tree Physiol 22:775-784.

Medhurst JL, Beadle CL (2001) Crown structure and leaf area index development in thinned and unthinned *Eucalyptus nitens* plantations. Tree Physiol 21:989-999.

Medhurst JL, Beadle CL (2005) Photosynthetic capacity and foliar nitrogen distribution in *Eucalyptus nitens* is altered by high-intensity thinning. Tree Physiol 25:981-991.

Medhurst JL, Beadle CL, Neilsen WA (2001) Early-age and later-age thinning affects growth, dominance, and intraspecific competition in *Eucalyptus nitens* plantations. Can J Forest Res 31:187-197.

Mendham DS, Grove TS, O'Connell AM, Rance SJ (2008) Impacts of inter-rotation site management on soil nutrients and plantation productivity in *Eucalyptus globulus* plnatations in South-Western Australia. In: Nambiar EKS (Ed.), Site management and productivity in tropical plantation forests. Proceedings of Workshops in Piracicaba (Bazil) 22-26 November 2004 and Bogor (Indonesia) 6 - 9 November 2006. Center for International Forest Research (CIFOR), pp. 64 - 79.

Mendham DS, Hardiyanto E, Sjarkowi F, Nurudin M, Soeprijadi D, Wicaksono A, Untung S, White D, Drake P, Rimbawanto A (2010) Realising genetic gains in Indonesia and Australian plantations through water and nutrient management: Final Report ACIAR Project FST/2004/058. Australian Centre for International Agricultural Research, ACIAR, GPO Box 1571, Canberra ACT 2601, Australia, p 87.

Mendham DS, Kumaraswamy S, Balasundaran M, Sankaran KV, Corbeels M, Grove TS, O'Connell AM, Rance SJ (2004) Legume cover cropping effects on early growth and soil nitrogen supply in eucalypt plantations in south-western India. Biol Fertil Soils 39:375-382.

Mendham DS, O'Connell AM, Grove TS, Rance SJ (2003) Residue management effects on soil carbon and nutrient contents and growth of second rotation eucalypts. Forest Ecology and Management 181:357-372.

Mendham DS, Sankaran KV, O'Connell AM, Grove TS (2002) *Eucalyptus globulus* harvest residue management effects on soil carbon and microbial biomass at 1 and 5 years after plantation establishment. Soil Biology & Biochemistry 34:1903-1912.

Mendham DS, White DA, Battaglia M, McGrath JF, Short TM, Ogden GN, Kinal J (2011) Soil water depletion and replenishment during first- and early second-rotation *Eucalyptus globulus* plantations with deep soil profiles. Agricultural and Forest Meteorology 151:1568-1579.

Messina MG (1992) Response of Eucalyptus regnans F. Muell. to thinning and urea fertilization in New Zealand. Forest Ecology and Management 51:269-283.

Morris AR (2008) Realising the benefit of research in eucalypt planttaion management. Southern Forests: a Journal of Forest Science 70 (2):119 - 129.

Myers BJ (1988) Water stress integral-a link between short-term stress and long-term growth. Tree Physiology 4:315-323.

Nambiar EKS (1990) Interplay between Nutrients, Water, Root-Growth and Productivity in Young Plantations. Forest Ecology and Management 30:213-232.

Nambiar EKS (2008) Site management and productivity in tropical plantation forests. In:0 Proceedings of Workshops in Piracicaba (Bazil) 22-26 November 2004 and Bogor (Indonesia) 6 - 9 November 2006 Ed. Nambiar EKS. Center for International Forest Research p237.

Nambiar EKS, Cossalter C, Tiarks AE (1998) Site management and productivity in tropical plantation forests: workshop proceedings, 16-20 February 1998, Pietermaritzburg, South Africa. Center for International Forestry Research.

Nambiar EKS, Harwood CE (2014) Productivity of acacia and eucalypt plantations in Southeast Asia. 1. Bio-physical determinants of production: opportunities and challenges. International Forestry Review 16:225-248.

Nambiar EKS, Harwood CE, Kien ND (2015) *Acacia* plantations in Vietnam: research and knowledge application to secure a sustainable future. South Forests 77:1-10.

Nambiar EKS, Kallio MM (2008) Increasing and sustaining productivity in subtropical and tropical plantation forest: Making a difference through research partnership. In: Nambiar EKS (Ed.), Site management and productivity in tropical plantation forests. Proceedings of Workshops in Piracicaba (Bazil) 22-26 November 2004 and Bogor (Indonesia) 6 - 9 November 2006. Center for International Forest Research (CIFOR), pp. 205 - 227.

Nambiar EKS, Sands R (1993) Competition for water and nutrients in forests. Can J For 23:1955-1968.

Nambiar EKS, Tiarks AE, Cossalter C, Ranger J (2000) A progress report. In: Namniar EKS, Tiarks A, Cossalter C, Ranger J (Eds.), Site management and productivity in tropical plantation forests. Workshop Proceedings 7-11 December 1999, Kerala, India. Center for International Forestry Research.

Nghia NH (2003a) Development of *Acacia* species in Vietnam. Agriculture Publishing House, Ha Noi:121 p.

Nghia NH (ed) (2003b) Development of *Acacia species* in Vietnam. Agriculture Publishing House, Ha Noi.

Nghia NH, Chien NV, Thu PQ (2010) Research to select *Acacia* and *Ecalyptus* clones for desease resistance and high-yeilding for commercial plantations. In:0 Ministerial level projects, phase 2: 2006 - 2010. Scientific Report. Forest Science Institute of Vietnam, p 12.

Nghia NH, Kha LD (1998) Selection of *Acacia* species and provenances for planting in Vietnam. In: Turnbull JW, Crompton HR, Pinyopusarerk K (Eds.), Recent developments in *Acacia* planting. ACIAR proceedings no. 82. Australian Centre for International Agricultural Research, Canberra, pp. 130-135.

Nguyen Hoang Nghia, Le Dinh Kha (1998) Species and provenance trials of acacias. In:0 Results of scientific research on silviculture in Vietnam, Ha Noi - Vietnam.

Norisada M, Hitsuma G, Kuroda K, Yamanoshita T, Masumori M, Tange T, Yagi H, Nuyim T, Sasaki S, Kojima K (2005) *Acacia mangium*, a nurse tree candidate for reforestation on degraded sandy soils in the Malay Peninsula. Forest Science 51:498-510.

O'Hehir JF, Nambiar EKS (2010) Productivity of three successive rotations of P. radiata plantations in South Australia over a century. Forest Ecology and Management 259:1857-1869.

O'Loughlin E, Nambiar EKS (2001) Plantations, Farm Forestry and Water: A Discussion Paper. Rural Industries Research and Development Corporation 01/137:36.

Otieno DO, Schmidt MWT, Adiku S, Tenhunen J (2005) Physiological and morphological responses to water stress in two *Acacia* species from contrasting habitats. Tree Physiol 25:361-371.

Pallardy SG (2008a) Chapter 5 - Photosynthesis Physiology of Woody Plants (Third Edition). Academic Press, San Diego, pp 107-167.

Pallardy SG (2008b) Chapter 10 - Mineral Nutrition Physiology of Woody Plants (Third Edition). Academic Press, San Diego, pp 255-285.

Pallardy SG (2008c) Chapter 12 - Transpiration and Plant Water Balance Physiology of Woody Plants (Third Edition). Academic Press, San Diego, pp 325-366.

Paul KI, Polglase PJ, Nyakuengama JG, Khanna PK (2002) Change in soil carbon following afforestation. Forest Ecology and Management 168:241-257.

Phat CD (2011) Report of the 5 million hectars reforestation program and plan for forest protection and reforestation period 2011-2020. Ministry of Agriculture and Rural Development Hanoi, p 33.

Pinkard EA, Beadle CL, Davidson NJ, Battaglia M (1998) Photosynthetic responses of *Eucalyptus nitens* (Deane and Maiden) Maiden to green pruning. Trees-Struct Funct 12:119-129.

Poorter H, Werf A, Atkin OK, Lambers H (1991) Respiratory energy requirements of roots vary with the potential growth rate of a plant species. Physiol Plantarum 83:469-475.

Quentin AG, O'Grady AP, Beadle CL, Mohammed C, Pinkard EA (2012) Interactive effects of water supply and defoliation on photosynthesis, plant water status and growth of *Eucalyptus globulus* Labill. Tree Physiol 32:958-967.

Rayment GE, Higginson FR Rayment GE, Higginson FR (ed) (1992) Australian laboratory handbook of soil and water chemical methods. Inkata Press Pty Ltd, Melbourne, Australia.

Ribet J, Drevon J-J (1996) The phosphorus requirement of N_2-fixing and urea-fed *Acacia mangium*. New Phytologist 132:383-390.

Richards AE, Forrester DI, Bauhus J, Scherer-Lorenzen M (2010) The influence of mixed tree plantations on the nutrition of individual species: a review. Tree Physiology 30:1192-1208.

Rietz D (2010) The effects of compaction and residue management on soil properties and growth of *Eucalyptus grandis* at two sites in KwaZulu-Natal, South Africa. University of KwaZulu-Natal, Pietermaritzburg, South Africa, p 362.

Ryan MG, Binkley D, Fownes JH, Giardina CP, Senock RS (2004) An experimental test of the causes of forest growth decline with stand age. Ecological Monographs 74:393-414.

Sam DD (2001) A scientific basis for silvicultural inputs to increase productivity of plantation forest. In:0 Research results on forest science and technology between 1996 - 2000. FSIV- APAFRI-TREELINK. Agriculture Publishing House, Ha Noi - Vietnam.

Sands P (1995) Modelling canopy production. II.* from single-leaf photosynthetic parameters to daily canopy photosynthesis. Aust J Plant Physiol 22:603-614.

Sang PM, Lamb D, Bonner M, Schmidt S (2012) Carbon sequestration and soil fertility of tropical tree plantations and secondary forest established on degraded land. Plant Soil 362:187-200.

Sankaran KV, Chacko KC, Pandalai RC, Balasundaran M, Grove TS, Mendham DS, O'Connell AM (2004) Influence of harvest residue management, weed control, legume cover cropping and soil trenching on *Eucalyptus* productivity in Kerala, India. Journal of Tropical Forest Science 16:232-247.

Schiavo JA, Busato JG, Martins MA, Canellas LP (2009) Recovery of degraded areas revegeted with *Acacia mangium* and *Eucalyptus* with special reference to organic matter humification. Science Agriculture 66:353-360.

Scholes RJ, Dalal R, Singer S Woomer PL, Swift MJ (ed) (1994) Soil physics and fertility: the effects of water, temperature and texture. John Wiley and Sons, Chichester.

Schönau APG (1981) Thinning research in *Eucalyptus grandis.* Wattle Res. Inst. Doc. 3/81:6.

Schönau APG (1984) A factorial thinning experiment in *Eucalyptus grnadis*. The Commonwealth Forestry Review 63:285-295.

Schönau APG, Coetzee J (1989) Initial spacing, stand density and thinning in eucalypt plantations. Forest ecology and management 29:245-266.

Shaohui F, Zuhui L, Longfu P, Xujing Y, Zongminh H, Zhiying H, Sizu L (2008) Effects of Site Management on Growth of a Second-rotation Chinese Fir. In: Nambiar EKS (Ed.), Site management and productivity in tropical plantation forests. Proceedings of Workshops in Piracicaba (Bazil) 22-26 November 2004 and Bogor (Indonesia) 6 - 9 November 2006. Center for International Forest Research (CIFOR), pp. 149-156.

Simard SW, Blenner-Hassett T, Cameron IR (2004) Pre-commercial thinning effects on growth, yield and mortality in even-aged paper birch stands in British Columbia. Forest Ecology and Management 190:163-178.

Sirega STH, Nurwahyudi, Mulawarman (2008) Effects of Inter-rotation Management on Site Productivity of *Acacia mangium* in Riau Province, Sumatra, Indonesia. In: Nambiar EKS (Ed.), Site management and productivity in tropical plantation forests. Proceedings of Workshops in Piracicaba (Bazil) 22-26 November 2004 and Bogor (Indonesia) 6 - 9 November 2006. Center for International Forest Research (CIFOR), pp. 93-106.

Smethurst P, Baillie C, Cherry M, Holz G (2003) Fertilizer effects on LAI and growth of four *Eucalyptus nitens* plantations. Forest Ecology and Management 176:531-542.

Smethurst PJ, Nambiar EKS (1990) Effects of Slash and Litter Management on Fluxes of Nitrogen and Tree Growth in a Young *Pinus radiata* Plantation. Canadian Journal of Forest Research 20:1498-1507.

Smith DM (ed) (1986) The Practice of Silviculture. New York: John Wiley and Sons, l986.

Smith RGB, Brennan P (2006) First thinning in sub-tropical eucalypt plantations grown for high-value solid-wood products: a review. Austtralian Forestry 69:305-312.

Snowdon P (2002) Modeling Type 1 and Type 2 growth responses in plantations after application of fertilizer or other silvicultural treatments. Forest Ecology and Management 163:229-244.

Squire R, Farrell P, Flinn D, Aeberli B (1985) Productivity of first and second rotation stands of radiata pine on sandy soils II. Height and volume growth at five years. Aust Forestry 48:127-137.

Sun JS, Sands R, Simpson RJ (1992) Genotypic variation in growth and nodulation by seedlings of *Acacia* species. Forest Ecology and Management 55:209-223.

Tang Z, Chambers JL, Sword MA, Barnett JP (2003) Seasonal photosynthesis and water relations of juvenile loblolly pine relative to stand density and canopy position. Trees 17:424-430.

Tiarks A, Ranger J (2008) Soil Properties in Tropical Plantation Forests: Evaluation and Effects of Site Management: a Summary. In: Nambiar EKS (Ed.), Site management and productivity in tropical plantation forests. Proceedings of Workshops in Piracicaba (Bazil) 22-26 November 2004 and Bogor (Indonesia) 6 - 9 November 2006. Center for International Forest Research (CIFOR), pp. 191-204.

Titshall L, Dovey S, Rietz D (2013) A review of management impacts on the soil productivity of South African commercial forestry plantations and the implications for multiple-rotation productivity. Southern Forests: a Journal of Forest Science 75:169-183.

Turnbull JW, Midgley SJ, Cossalter C (1997) Tropical acacias planted in Asia: an overview. In: Recent developments in acacia planting. Hanoi. ACIAR, pp. 14-28.

Turnbull TL, Adams MA, Warren CR (2007) Increased photosynthesis following partial defoliation of field-grown *Eucalyptus globulus* seedlings is not caused by increased leaf nitrogen. Tree Physiol 27:1481-1492.

van Reewijk LP (ed) (2002) Procedures for soil analysis (6th ed.). Technical Paper No. 9

Pbulisher.

Vitousek P (1982) Nutrient Cycling and Nutrient Use Efficiency. The American Naturalist 119:553-572.

Vitousek PM (1984) Litterfall, Nutrient Cycling, and Nutrient Limitation in Tropical Forests. Ecology 65:285-298.

Vitousek PM, Turner DR, Parton WJ, Sanford RL (1994) Litter decomposition on the Mauna Loa environmental matrix, Hawai'i: patterns, mechanisms, and models. Ecology:418-429.

Walker TW, Syers JK (1976) The fate of phosphorus during pedegenesis. Geoderma 15:1-19.

Wang F, Li Z, Xia H, Zou B, Li N, Liu J, Zhu W (2010) Effects of nitrogen-fixing and non-nitrogen-fixing tree species on soil properties and nitrogen transformation during forest restoration in southern China. Soil Science and Plant Nutrition 56:297-306.

Wang JR, Simard SW, Kimmins JP (1995) Physiological responses of paper birch to thinning in British Columbia. Forest Ecology and Management 73:177-184.

Waring RH, Running SW (2007) Chapter 2- Water Cycle. In: Running RHWW (ed) Forest Ecosystems (Third Edition). Academic Press, San Diego, pp 19-57.

Webb MJ, Reddell P, Hambleton A, Robson K (2000) Growth response of four tropical plantation timber species to increasing phosphorus supply and assessment of phosphorus requirements using foliar analysis. New Forest 20:193-211.

West PW (ed) (2014) Growing Plantation Forests. Springer International Publishing Switzerland.

White DA, Battaglia M, Mendham DS, Crombie DS, Kinal J, McGrath JF (2010) Observed and modelled leaf area index in *Eucalyptus globulus* plantations: tests of optimality and equilibrium hypotheses. Tree Physiol 30:831-844.

White DA, Crombie DS, Kinal J, Battaglia M, McGrath JF, Mendham DS, Walker SN (2009) Managing productivity and drought risk in *Eucalyptus globulus* plantations in south-western Australia. Forest Ecology and Management 259:33-44.

Whitehead D, Beadle CL (2004) Physiological regulation of productivity and water use in *Eucalyptus*: a review. Forest Ecology and Management 193:113-140.

Wibisono MG, Veneklaas E, Mendham DS, Hardiyanto EB (2015) Nitrogen fixation of *Acacia mangium* Willd. from two seed sources grown at different levels of phosphorus in an Ultisol, South Sumatra, Indonesia. Southern Forests: a Journal of Forest Science 77:59-64.

Wiseman D, Pinkard E, Wardlaw T, Mohammed C, Hall M, Beadle C (2009) Growth responses of *Eucalyptus globulus* and *E. nitens* to pruning and fertiliser treatments in a plantation managed for solid-wood products. South Forests 71:21-29.

Worbes M (1999) Annual growth rings, rainfall-dependent growth and long-term growth patterns of tropical trees from the Caparo Forest Reserve in Venezuela. Journal of Ecology 87:391-403.

Xu D, Yang ZJ, Zhang NN (2004) Effects of site management on tree growth and soil properties of a second-rotation plantation of *Eucalyptus urophylla* in Guangdong province, China. In: Nambiar EKS, Ranger J, Tiarks AE, Toma T (Eds.), Site management and productivity in tropical plantation forests. Proceedings of Workshops in Congo July 2001 and China February 2003. Center for International Forest Research (CIFOR), pp. 45-60.

Xu DP, Dell B Wei RP, Xu D (ed) (2003) Nutrient management of eucalypt plantations in South China. World Scientific Publ Co Pte Ltd, Singapore.

Xu DP, Yang J, Zhang NN (2008) Effects of Site Management on Tree Growth, Aboveground Biomass Production and Nutrient Accumulation of a Second-rotation Plantation of *Eucalyptus urophylla* in Guangdong Province, China. In: Nambiar EKS (Ed.), Site management and productivity in tropical plantation forests. Proceedings of Workshops in Piracicaba (Bazil) 22-26 November 2004 and Bogor (Indonesia) 6 - 9 November 2006. Center for International Forest Research (CIFOR), pp. 39-50.

Yang L, Liu N, Ren H, Wang J (2009) Facilitation by two exotic acacias: *Acacia auriculiformis* and *Acacia mangium* as nurse plants in South China. Forest Ecology and Management 257:1786-1793.

Yao RL, Glencross K, Nichols JD (2014) Difference in shade tolerance affects foliage–sapwood response to thinning by two eucalypts. Southern Forests: a Journal of Forest Science 76:93-100.

Zinn YL, Resck DVS, Silva JEd (2002) Soil organic carbon as affected by afforestation with *Eucalyptus* and *Pinus* in the *Cerrado* region of Brazil. Forest Ecology and Management 166:285 - 294.

Appendix

This article has been removed for copyright or proprietary reasons.

Southern Forests: a Journal of Forest Science
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tsfs20

Improving productivity and sustainability of successive rotations of Acacia auriculiformis plantations in South Vietnam

Vu Dinh Huong[ad], EK Sadanandan Nambiar[b], Le Thanh Quang[a], Daniel S Mendham[c] & Pham The Dung[a]

[a] Forest Science Institute of South Vietnam, Ho Chi Minh City, Vietnam
[b] CSIRO Land and Water Flagship, Canberra, Australian Capital Territory, Australia
[c] CSIRO Land and Water Flagship, Hobart, Tasmania, Australia
[d] School of Land and Food, University of Tasmania, Hobart, Tasmania, Australia
Published online: 23 Dec 2014.